BEYOND THE DEEP FIELD

Hubble's Legacy and the Future of Cosmic Observation

SYMPOSIUM TRANSCRIPT

June 4–5, 2026 | Washington, DC

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Opening Remarks

Speakers

Brian Odom, NASA Chief Historian
Jared Isaacman, NASA Administrator
Mark Clampin, Deputy Associate Administrator, Science Mission Directorate

Odom: Good morning everyone, and welcome to NASA Headquarters for our symposium, Beyond the Deep Field: Hubble's Legacy and the Future of Cosmic Observation. I'm Dr. Brian Odom, I'm the NASA chief historian. I'm super excited about this event. On behalf of NASA, the History Office, our partners in SMD, the Hubble program, everyone who helped organize this symposium, thank you for joining us over the next day and a half. We are especially pleased to welcome the scientists, engineers, and historians who have gathered to reflect on one of the most remarkable achievements in history of science and space exploration, the Hubble Space Telescope. As this is our second attempt at this event, I appreciate everyone's willingness to hang in there with us in there as we celebrate now 36 years, so even better.

It was 36 years ago, on 24th April 1990, that Hubble began its journey aboard the Space Shuttle Discovery, but its story started much earlier, with ambitious ideas about what could be accomplished with a telescope if placed above Earth's atmosphere. In fact, it was 80 years ago, in 1946, that Lyman Spitzer published his influential report, *Astronomical Advantages of an Extra-Terrestrial Observatory*. There, Spitzer underscored that the "practical problems of operating such a large installation would, of course, be enormous." But Spitzer also emphasized that an instrument this powerful had the potential to "uncover new phenomena not yet imagined, and perhaps to modify profoundly our basic concepts of space and time." So, from the beginning, advocates of the program understood both the challenges involved and the rewards that success might bring.

Hubble's development happened against the backdrop of a dizzying array of technological achievements. When he published his 1946 report, the United States had just figured out the mass production of penicillin. The microwave oven, the Slinky, and commercial television were also making their first appearances in living rooms across the country, so it was quite a time. By the time Hubble launched in 1990, home computing, the World Wide Web, and personal cell phones were becoming the defining features of the technological landscape. It's hard to imagine what would have dazzled Spitzer more—the breathtaking views of the cosmos that Hubble was eventually to reveal or the fact that high school students can look them up instantly on a smartphone.

Few missions had become so deeply woven into both the scientific enterprise and popular culture as Hubble. It has truly transformed humanity's view of the universe. Its observations helped refine our understanding of the age and expansion of the cosmos, contributed to the discovery of dark energy, revealed the diversity of planetary systems beyond our own, and provided countless new questions for future generations to explore. Yet Hubble's significance extends beyond science alone. Hubble is also a story about institutions and people. It is a story about how governments, universities, industry partners, international organizations, astronauts, engineers, and scientists worked closely across decades to accomplish something extraordinary. It is a story about resilience, nowhere perhaps more evident than in that initial response to the mirror flaw discovered shortly after launch and the remarkable efforts that shifted what could have been a historic failure into one of NASA's greatest success stories.

But no program stands alone. Hubble was the cornerstone of NASA's monumental Great Observatories program, a group that included, as you all know, Compton Gamma-ray Observatory, Chandra X-ray Observatory, and the Spitzer Space Telescope. Together, these observatories established the era of multiwavelength astronomy and forever altered our perception of the cosmos.

Enter the historians. Historians are particularly interested in turning points, moments when the future could've gone a vastly different direction. The history of Hubble is filled with many of those critical decision points. There was the decision to build it in the first place, the decision to divide up center responsibilities before development, the decision to make it serviceable, and the decision to cancel then put back on the books that final fifth servicing mission that took place in 2009. As historians, we are also interested not only in what actually happened, but also in drawing lessons from past experiences for application to current and future missions. For us, this is the central purpose of this symposium.

Over the next two days, we will examine Hubble from multiple perspectives. We will explore its origins and development, its scientific achievements, the partnerships that sustained it, and the ways in which Hubble shaped later observatories, such as Webb Telescope and future flagship missions still on the horizon. Our goal is not simply to celebrate Hubble's accomplishments; although, there is certainly much there to celebrate. Rather, just consider what Hubble history can teach us about the future of scientific discovery, technological innovation, and exploration.

I want to offer my sincere thanks to everyone who made this event possible. Organizing a symposium like this requires a tremendous amount of effort from people across NASA and our partner institutions. From our planning team and logistical staff to our moderators, panelists, speakers, and tech support, thank you for contributing your time, expertise, and enthusiasm. We are particularly grateful to those who spent decades building, operating, maintaining, studying, and documenting Hubble. Your work is the reason we are able to have these conversations today. The discussions that occur over the next day and a half will help ensure that Hubble's legacy is not only remembered but also understood in ways that can inform future generations of explorers and researchers. It's now my pleasure to introduce two NASA leaders who both play critical roles in shaping NASA's present and future scientific endeavors. First, please join me in welcoming to the stage the 15th administrator of NASA, Jared Isaacman, Administrator.

Isaacman: Well, good morning, everyone, and thank you, Brian, thank you for the introduction. Thanks for everyone joining us today. I tell you absolutely, I love this subject. I would enjoy sitting here with all of you over the next couple of days just to unpack all these great accomplishments of this great exploration asset.

And on that note, for 36 years, the Hubble Space Telescope has informed and enlightened humanity's understanding of the universe. Today, it travels at 17,500 miles per hour and has covered the distance equivalent to a trip to Neptune and gazed 13.4 billion years into the universe's earliest light. It's contributed to the discovery of dark energy. It's transformed our understanding of black holes, and galaxies, and star formation, and planetary systems, generating more than a million observations and tens of thousands of scientific papers. Entire careers have been built on the discoveries made possible by this observatory, not to mention all the inspired and curious people across the world that have been captivated by the thought-provoking imagery. It's impossible, I think, to overstate all that Hubble has done for our collective understanding of the universe and our place in it.

And while the world may know Hubble from its now iconic images, people don't often know about the workforce, the brilliant engineers and scientists, alongside all the resources that have gone into launching, and maintaining, and studying one of the world's greatest exploration assets. We have learned so much from our first major orbital telescope. Hubble taught NASA how to build, operate, maintain, service, upgrade, and sustain the flagship observatory over many decades. Oh, excuse me. If we rewind the clock to 1990, the observatory was expected to operate for roughly 15 years. Instead, NASA adapted to unexpected developments. We solved problems, we flew five astronaut servicing missions and continuously improved the observatory through extraordinary engineering and perseverance; we were doing what NASA does. And now 36 years later, Hubble continues to expand humanity's understanding of the universe. That's an incredible achievement.

The lessons learned from Hubble helped inform other great instruments of science, including the Chandra X-ray Observatory and the James Webb Space Telescope, and are currently being applied to the Nancy Grace Roman Space Telescope today and will surely help shape the Habitable Worlds Observatory in the years ahead. NASA's success in designing, launching, servicing, and sustaining Great Observatories comes from the same iterative, evolutionary playbook that carried America to the Moon during the Apollo era and is now guiding our return during the Artemis era. Each mission builds upon the lessons of the last, expanding our capabilities and making the next breakthroughs possible.

Up next in just a few months, Nancy Grace Roman Space Telescope will launch and travel nearly 1 million miles away from Earth to unlock new discoveries, to evolve our understanding of the universe, and carry the spirit and the inspiration of Hubble forward for the next generation of engineers, astronomers, and dreamers. Beyond Roman lies the Habitable Worlds Observatory, a mission that could help answer the question people have been thinking about since the beginning of human history. And as I've said many times, NASA does not exist to be a caretaker of history, but to make history, and as such, we have a responsibility to always be thinking about and investing in what comes next. That means being disciplined and efficient with the resources the American taxpayers have entrusted us with, maximizing the scientific value of every dollar available, both with the missions of the past that still yield amazing data and the missions of the future that have the potential to change, well, maybe everything.

The success of Hubble and all of our observatories make it clear that science and discovery will always remain at the heart of NASA's mission, delivering the kinds of headlines that only NASA is capable of achieving. So, as we reflect on Hubble's remarkable contributions over the next two days, I hope we spend as much time discussing the future as we do celebrating the past, because the great adventure that we are all on together is only just beginning. So, thank you, and I hope you enjoy the symposium.

Odom: Thank you, Administrator. Next, we'll hear from Dr. Mark Clampin, deputy associate administrator in NASA's Science Mission Directorate and a longtime leader in space astronomy himself. Dr. Clampin.

Clampin: So, thank you, Administrator Isaacman. I'm also happy to welcome you all today to celebrate the incredible legacy of the Hubble Space Telescope, and I'm really pleased to see a lot of friends out there going all the way back to Servicing Mission 1, which I was involved with.

So, Hubble's taken over 1.7 million observations to date. That's almost 29,000 astronomers who have published peer-reviewed science papers using Hubble data, resulting in about 24,000 publications. It's not exaggeration to say that Hubble has changed mankind's understanding of the universe. And Hubble's servicing missions with the upgrades to the instrumentation that came with each mission really enabled us to realize both Hubble's true potential by fixing initially the aberration but then following with decades of groundbreaking discoveries.

I think while Hubble has changed almost every field in astrophysics, its most notable observation is undoubtedly the Hubble Deep Field, first observed in 1995. And the Hubble Deep Field fundamentally changed our understanding of the early universe, and I think it's really important to note that it began with discussions at Science Coffee mornings at the Space Telescope Science Institute as the instrument scientists working on WFPC2 started to note that they were seeing strange things in some of the very deep images that were being taken, I think starting with parallel fields. And that then, of course, led to Bob Williams, Space Telescope Science Institute director in '95, really demonstrating the ideal of scientific leadership by deciding to undertake this high-risk, high-reward observation. And I think it's really also important to note that the Hubble Deep Field is really the validation of the National Academy's Hornig Report, which laid out the plan for how we should do science operations with large flagship missions. So, if you haven't read the Hornig Report, I encourage you to go back and read it. It was written long before we had PDF, so it's quite a read.

I also want to just mention, of course, that Hubble Deep Field also led to Webb Telescope. And once we had the first results on the Hubble Deep Field, the case for Webb became pretty much overwhelming. We would have to break that 1 billion year after the Big Bang barrier by going into the near infrared, so it's also the father of the Webb Telescope.

Now, one thing that always catches me a bit is that many of the early discoveries that Webb—as far the Hubble made are now taken for granted, mainly because Hubble has been operating for so long. And some examples include being able to precisely measure the universe's expansion rate or the Hubble constant. Remember, before we launched Hubble, they were still arguing whether it's 50 or a hundred. That's the kind of impact it had on the field. We were able to find and measure the mass of supermassive black holes at the center of galaxies, and we were able to use the transiting technique to make the first spectroscopic observations of the atmospheres of exoplanets. And I don't normally remember telephone numbers, but I do know the very first transit observation was a gas giant called HD 209458. And that observation was made by a very long list of collaborators, but notably Ron Gilliland at Space Telescope and, of course, Dave Charbonneau, who recently won the Kavli Prize for this kind of work. And now more recently, Hubble's also been able to directly image young exoplanets that are still cooling and thus can be seen in the near infrared with the near-infrared camera on Wide Field 3.

And, of course, Hubble contributed to the discovery of dark energy. This is that mysterious phenomena that's accelerating the expansion of the universe. And, of course, that led to the Nobel Prize in Physics, which was awarded to Adam Riess, who worked at Space Telescope Science Institute, of course, in Johns Hopkins, and Saul Perlmutter and Brian Schmidt. And that also established the thread that led to the science that we're going to be doing with the Nancy Grace Roman Telescope, which we hope to launch this year at the end of the summer. So, since 2022, I think that researchers have regularly combined Hubble's observations with those from Webb, and we'll be able very soon to dive into the near-infrared datasets that come from the Roman Space Telescope as well.

I think it's also important to note—and the administrator touched on this—the future of discovery and exploration really has to be sustainable and build on Hubble's model. And what I mean by sustainable in this context is that we want the systems and the spacecraft to be repairable and refuellable in the future, and I'm specifically talking about large flagships here. So, as we think about the next generation, those are key themes. And many of you will have heard early talks on the Habitable Worlds Observatory where we really are focused on those themes. It's been 17 years now since Hubble's last servicing mission, so as the administrator noted, we really have to start looking at legacy science operations and find ways to find cost savings in operations as we prepare for the next generation of flagship missions.

So, looking to the future, Hubble's planned successor after Roman is the Habitable Worlds Observatory, which will hopefully have a significantly larger mirror than Hubble's and will study the universe in the visible and ultraviolet. And it will be really focused at following on from the legacy of Hubble by opening up the ultraviolet. We've really done that in the near infrared and the mid-infrared with Webb, but we still have to break that barrier with the ultraviolet. Habitable Worlds is going to survey about 300 stars and nearby Earth-like planets, and then we hope to study their atmospheres and look for evidence of life via biosignatures.

The other point I wanted to make before I step down is that in addition to the primary science goal, Hubble—sorry, the Habitable Worlds Observatory will also advance science across all astrophysics, much the same way that Hubble has done and the Webb Telescope after it. It's not just one science goal observatory; it will address a whole range of different science goals. I think it's also notable that as you look at the legacy of Hubble, we remember that a lot of scientists who started their careers working on Hubble have gone on to be leaders in the astrophysics community, have helped lead the Webb program and now more recently, the Roman program. And we hope that that legacy will continue on into the era of Habitable Worlds.

The other big takeaway that I want you to go away with and also take to the first couple of panel discussions is that Hubble's impact goes way beyond just the astrophysics discoveries. It drove a lot of new technological breakthroughs, especially in the field of sensors, and I think that's a lasting legacy not just for astrophysics but for the nation. Because most of you have cell phones, I'm sure, in your pocket, and a lot of the early work done and the investments done for Hubble with Texas Instruments gave us those CCDs that were the first couple of generations, for instance, of iPhone camera sensors. So, the technology that we developed for Hubble has really seeped out into our popular culture, much the same way that the images that Hubble has delivered have also done the same. So, to finish up, I just want to thank everybody who's ever worked on Hubble for your hard work in making this mission a success, and I'm really looking forward to the discussions today, thank you.

Session One

Histories of the Hubble Space Telescope

Moderator

Lois Rosson, NASA

Panelists

Robert Smith, University of Alberta
Patrick McCray, University of California, Santa Barbara
Rebecca Charbonneau, American Institute of Physics

Rosson: Thank you all so much for joining us and thank you to all of our participants for taking the time to participate in this symposium. My name is Dr. Lois Rosson. I am a historian in the NASA History Office, where I am assigned to the Habitable Worlds Observatory. Occasionally, when I tell my other historian friends that I am historicizing a telescope that does not exist yet, they ask me how I do that. I think that this is a crowd that is uniquely primed to understand the immense amounts of labor and decision-making that happen in the decades before these technologies launch.

It is my great honor to introduce this very special panel, which is the only panel made up of exclusively historians at the symposium, who I think are going to be able to offer us some unique perspectives on the Hubble Space Telescope as an object in history. First, we have Professor Robert Smith, who is at the University of Alberta in Edmonton, Canada. He has written extensively on the history of modern astronomy, including a book that many of you probably know, *The Space Telescope*, which is an award-winning history of Hubble's early development and also a testament to the long cook time of these tools. The book was published a year before the launch of the Hubble Space Telescope because there was that much material to put in a lengthy and thorough account. Robert has also written three popular books with David DeVorkin who we also have the pleasure of having here in the audience.

We have Dr. Rebecca Charbonneau, who is a historian of science at the American Institute of Physics, where she leads the institute's astrophysics initiative, including a major project documenting the history of exoplanet research, which, Rebecca, I'm hoping you'll tell us a little bit more about. She also serves as an adjunct assistant scientist at the National Radio Astronomy Observatory. And her first book, *Mixed Signals: Alien Communication Across the Iron Curtain*, was published in 2024 and was listed as a best book by both the *Financial Times* and the *New Yorker,* so I definitely recommend that as well.

And it's also my pleasure to welcome Professor Patrick McCray, who teaches at the University of California at Santa Barbara. He's written extensively about the history of modern astronomy and its data practices. I use his book *Giant Telescopes* all the time in my own work. He is a very prolific historian of technology and science, and most recently, has been posted up at the Library of Congress as the Kluge Chair in Technology and Society.

Thank you all so much for joining us. To kick us off, I know I just gave a very basic introduction of your work in the history of astronomy, but I was wondering if you could tell us a little bit more about your research and how it has intersected with the Hubble Space Telescope? How do historians interact with an object like this? Rebecca, maybe let's start with you?

Charbonneau: Hi everyone. So, I am predominantly a radio astronomy historian. I got my start at the University of Cambridge, which is where I earned my PhD in history and philosophy of science, followed by some work at—a postdoc at the Harvard-Smithsonian Center for Astrophysics, and then a Jansky Fellowship at NRAO, where I've retained affiliation since then. Really, most of my work has covered the history of radio astronomy from the 1950s, '60s, and '70s, so well before Hubble, not optical astronomy. But I'm here to provide a little bit of a compare-contrast perspective and also look at the Hubble Telescope as part of the legacy of Big Science, big astronomy projects as they culminated from the mid-20th century on into the '90s and into the 21st century.

Hubble, even though it was launched in the 1990s, it has a history that stretches far back, even back with Lyman Spitzer predicting it in 1946 before there were any human-made objects in space. And so even though I have not engaged directly with Hubble in my work, I can see the importance of its legacy as it impacts fields like the development of exoplanet science, which I'm hoping to get into a little bit later, but also the acceleration of multiwavelength, multimessenger astronomy, which we see really transformed the way astronomy was practiced in the late 20th and into the 21st century.

Rosson: Patrick, maybe you can answer next?

McCray: Yeah, hi, good morning. So, I'm a historian of science and technology. I started my career by writing a history about ground-based telescopes in the latter half of the 20th century. And it's really interesting to look out at the folks here, and I see many people that I interviewed for that project. And at that same time, I was also working with Robert Smith, the very early stages of documenting what, at the time, was called the Next Generation Space Telescope, now of course, the James Webb Space Telescope.

One of the things that I was really interested in was the question of how new technologies change the practice of doing astronomy and change the professional identity of what being an astronomer is. Dr. Clampin mentioned this in his opening remarks, about things that we take for granted. And one of the things that I've been interested in are the changing practices associated with data collection, data archiving, processing of data, and things like that, and we can say more about that as time goes by. But I think that this is one of the things that has shaped the nature of how scientists go about doing their jobs on a daily or nightly basis, so.

Smith: I'm Robert Smith. I had the privilege of following Hubble pretty much full time from 1983 through the first half of 1987, and then following Hubble history, not on a full-time basis, but on a part-time basis for several years after that. And so, I was, what would have been called in World War II, a combat historian. I would go to meetings and sit in on science working group meetings. I would do lots of interviews. I was there when Dr. Fisk gave his Deckchairs on the Titanic speech, which I hope we will be hearing about a bit later for example. And so, it was a different kind of history from the sort of history I'd done earlier, which had been very much document-based. And I like to joke that one advantage of document-based history is everybody's dead; they can't argue back. But what I found was it was actually exceptionally useful to be able to interview people and iterate towards establishing what actually happened in ways that, as I envisaged it, in 50 years' time, this stuff will not be available to anybody. And so, I thought it was immensely valuable to have a historian around to see what was going on and to document that.

And so there was a very large collection, for example, of oral history interviews, which I conducted, which are in the collection of the National Air and Space Museum, and they're available to other scholars and researchers. There was a lot of material I saved because one of the major issues in, say, contemporary history of science and technology is the sheer volume of stuff. What do you save? And everybody thinks everybody else has been saving stuff, but they haven't. And so there was a large repository of documents, too, that I was able to deposit at the Smithsonian. And I worked very closely with a number of colleagues at the Smithsonian, too, who helped tuned me in how to do this kind of history. So, I was in a very fortunate position in that sense.

Rosson: The practice of astronomy is one that deals with immense timescales. I'm wondering if you guys can help us put the Hubble Space Telescope in a broader context? Specifically, if there are any historical backdrops that we don't typically associate with the Hubble Space Telescope, but that did come to bear on the development of the telescope, or its operations? What do we *not* think about when we think about the development of this tool, that did help shape its trajectory? Robert, maybe we'll start with you on this question.

Smith: One of the things that was very evident when I began researching the development and history of Hubble was the importance of what you could call coalition building. You just can't have a bunch of astronomers saying, "Yes, oh, that would be nice, let's build that," or a small group in NASA saying, "Yes, please, let's go and spend billions of dollars on this telescope." It really is a very complex process of bringing together institutions, people making a project not just scientifically feasible, but also technically, politically feasible. And so, I spent a lot of time looking at that development of coalition building, and the sheer importance of negotiations, figuring out what you could do, if you can't do everything, what is it we can achieve. Originally, for example, the mirror size for Hubble was going to be 3 meters, but that wasn't going to work because the Congress said, "That's going to be too expensive." Congress also said, "Look, you've got to go off and get some international participation," and so we end up with Hubble Space Telescope, which has a primary mirror of 2.4 meters in diameter. The European Space Agency ended up with a 15 percent contribution as well.

And, certainly when I started off, I thought I was going to be doing history of astronomy, and it was much broader than that. Because if you ask the basic question, how do you move from the idea in somebody's head to the drawing board to getting something in orbit, it is an amazingly complex process, and it requires great skills to bring that about. And so, the astronomy that flowed from that was not a simple process, but I think often the public have the impression that somehow, the stuff gets built, and it's all straight forward, and then you get the result. It's a hugely challenging and difficult process of making it happen, and it takes time to do that.

Rosson: Great, thank you. Patrick?

McCray: Yeah, so I think my interests, in some ways, lie at the opposite end of what Robert was talking about, where he's talking about the processes that lead up to a science facility being built. My interests lie more in terms of how these facilities are used and how this shapes the nature of how science is done. And in the archival research that I've done and then in the many oral histories that I've done, similar to what Robert was talking about, there are just lots of parallels that one sees between both ground-based observing and space-based observing. But to my mind, the most significant change in terms of how these facilities are used has to do with the changing norms and practices associated with data. And how it's collected, how it's processed, how it's archived, but perhaps most importantly, how it's shared.

And for those of you who are old enough to remember the nature of astronomy in the '60s, '70s, into the '80s, the idea of an astronomer in his or her office with stacks of glass plates of photographs that they had collected or perhaps data tapes that were theirs that were not publicly available. They were not put into a public archive, and they were very much viewed as private property. And I think with facilities like Hubble, with national observatories like the Gemini Observatories, those practices have changed, and now, you have publicly accessible databases. But the amount of work that goes into creating those, again, is oftentimes hidden and unrecognized. I mean, just the idea of creating, which seems like a fairly dull topic, but data standards for being able to share files between one observatory and another in the 1970s and 1980s. Again, practices that today amongst astronomers are just seen as commonplace, that this is the way science is done. But to recognize that a lot of work and a lot of effort, and like Robert said, a lot of coalition building had to go into the process of creating those practices that today's graduate students and postdocs in astronomy would take for granted.

Charbonneau: Just to follow up on your point before I make my own, it's also just the distance between the astronomer and the instrument, in a very literal sense, the Hubble Space Telescope, and that you cannot directly observe from it. But it was part of a major shift that started happening around that time where astronomers no longer directly engaged with instruments. I've spent a lot of time at NRAO hanging out with the octogenarians of the Office of the Retirees and Emeriti Staff, the people historians like to hang out with. And they often complain to me that around the same time that they were not able to continue to work on their cars, they were not able to work on their telescopes, and so there was an interesting divide there.

But when I think about Hubble and shifting historical context in astronomy, the first thing that really comes to mind, which I've alluded to already, is the acceleration of the disciplinary shift from people really being in one kind of wavelength camp or division into really working across the electromagnetic spectrum. For most of the 20th century, you did have stark division, not only amongst the way astronomers practiced, but even in the ways they were trained. Just my own background in radio astronomy, if you look at when the field was developing in the '40s, '50s, and '60s, a lot of the astronomers didn't even have backgrounds in astronomy, they were radio engineers or radio physicists. A lot of them had served during World War II as radar operators and fell backwards into astronomy because of the strange signals that they might have seen on some of their instruments they were using.

And it really wasn't until the late 20th century and early 21st century that because of instruments like Hubble, it really accelerated that shift, and partly, it's because of some happy coincidences. If you look at other instruments like the VLA, for example, they have roughly the same angular resolution as the Hubble Telescope, and so you're able to physically overlay images—data quite easily and see the same physical structures and the same angular resolution. I think the canonical example of this is Hercules A, where you have Hubble's optical images of the galaxy overlaid on top of the VLA's radio jets. And it's because of possibilities like that that you really have a cultural shift in a whole new generation of astronomers who become very comfortable working across the electromagnetic spectrum.

And it's always quite funny to me as someone who spends most of her days in the 1960s, when I walk through the halls of places like NRAO, few people there would consider themselves as radio astronomers like they did in the 1960s. But they see themselves just as astronomers or astrophysicists because we really have lost a lot of those disciplinary boundaries when it comes to the wavelengths we study.

Rosson: That was great, thank you. Rebecca, maybe you can tee off our next question too, which is how did Hubble impact the telescope architectures that came after it? How was its impact felt in ground-based observing, and maybe you can also tell us a little bit about your work in exoplanets?

Charbonneau: Sure, wow, that's a lot to tackle.

Rosson: Big question.

Charbonneau: Yeah, so just to start with its impact in ground-based observing, I think a lot of that I've already covered, which is there was an impetus, especially when designing instruments, to keep in mind the technical infrastructure of other telescopes, including space-based telescopes, as we were developing instrumentation. So that there could be easy cooperation and collaboration between data from multiple instruments. I think Hubble really highlighted the importance of—serendipity has always been important in the history of astronomy.

In my work in exoplanet science because of my background in radio, I always have a little bit of a pet favorite. So technically, the first exoplanet to be definitively detected was the multi-planet pulsar system detected by Aleksander Wolszczan and Dale Frail. Wolszczan was at Arecibo and Frail was at NRAO. And they were able to just make this detection using a combination of Arecibo and VLA. And this was in 1992, so right around when Hubble was launched. You could have made the argument that maybe exoplanetary science was going to be in the domain of radio, but then of course, you have in 1995, the detection by Mayor and Queloz of 51 Pegasi b. Shortly thereafter, you start getting what Dr. Clampin referred to earlier as the early exoplanetary atmospheric characterization that Hubble is able to do.

And so, seeing that rapid development of the field is really quite interesting because prior to Hubble being launched, there was no definitive proof that exoplanets existed at all. I mean we had a pretty strong expectation that they did, but there was no definitive evidence. And then just in those early few years, you have that rapid discovery and across wavelengths showing, highlighting again, the need for cooperation between space-based and ground-based telescopes.

And critically, the idea of biosignatures, again, didn't even really exist, and then here, Hubble was detecting what would eventually be atmospheric characterization, which is the bread and butter of biosignature research today. And so, building instruments and seeing what comes from them is one of the fun things of astronomy because just because you might have the expectation it will detect or discover something doesn't mean it happens. And so, Hubble in that sense was very lucky in that it launched at this beautiful acceleration in the detection of exoplanetary systems.

Rosson: Thank you. Patrick, Robert, either one of you want to weigh in on Hubble's impact on other telescope architectures, ground-based or otherwise?

Smith: Sure, so last week, I spent quite a bit of my time actually wondering about this question because I was looking at the development, early development of what was called the Next Generation Space Telescope, nw named the James Webb Space Telescope, and how it was influenced by Hubble. And my sense is, in a way, the early versions of what is called the Next Generation Space Telescope, Webb was almost an anti-Hubble. It's not so much you have A is followed by B, which is followed by C, so C must have been influenced by B and A. Well, not necessarily, if you look at the development, even if you go back to the development of Hubble itself, it's really the contractors and what they have done before that shapes, I think, what kind of spacecraft you end up with the Hubble Space Telescope.

With Webb, the NASA administrator, who plays an important role in this story, Dan Goldin, Goldin was hugely enthusiastic about the images of Hubble, the scientific results of Hubble. But his basic message was to challenge the engineers and say, "Look, we just can't keep on doing this kind of thing. It's just too expensive, there's going to be no shuttle launch, there's going to be no shuttle servicing by astronauts. The mirror for Hubble is just too heavy, we just can't scale up, we've got to find a much lighter kind of primary mirror material," and so on. And so, it's the reaction against Hubble, I think, that very much shapes those early NGST designs. And the Webb folks in the audience may want to argue with me, but that's how I would read things. And so, it's good to get away from some sort of linear model. And I suspect by the time that Habitable Worlds is built, it may well be, in part, in reaction against things to do with Webb that maybe need to be changed, that you end up with the final version of the spacecraft.

Rosson: And we will have a Q&A at the end if you do want to fight with Robert. Patrick, do you want to take a crack at that?

McCray: Yeah, I maybe take that in a different direction. So, Robert was talking about the Webb Space Telescope, and I'd make the suggestion that, in some ways, Hubble was the original Webb Telescope in the sense that it was launched in the 1990s. And the 1990s were very much the era of the Internet and the World Wide Web, and I think that's an important thing to keep in mind. Again, I'm going back to this idea of how data and images were being shared and circulated. And you had these new infrastructures of knowledge that were emerging and becoming both ubiquitous and global that allowed for the sharing and spread of both images for public consumption, the sorts of things that you would see on calendars and coffee cups. But also, allowing scientists to more readily share data using those different kinds of data infrastructures. And I think that synergy between the Hubble Space Telescope and the early iteration of the World Wide Web is something that's, together, a fairly profound combination.

Rosson: You have all started to allude to this, but I'm wondering if you could talk a little bit about how Hubble's story had changed over the last 36 years? What do you think that early commentators got right and what did they get wrong? How are we reflecting now in 2026 on this hardware?

McCray: So, one of the things that surprised me when I was doing the research and then collecting a lot of oral histories for what became the book that I wrote called *Giant Telescopes* was a prevailing sense, especially in the 1980s among the astronomy community. That space-based observatories would make ground-based ones unnecessary and obsolete. And this is something that you see over and over, both in private conversations that were recorded, and in correspondence and official reports. This idea that, in the 1990s, there would be no need for ground-based telescopes, that space-based telescopes would just put those facilities out of business, and that Hubble would do it all. And I think Robert could probably speak to this, but there were definitely people on the Hill who presented these ideas in congressional hearings and argued against the funding of the Hubble Space Telescope, especially as its costs continued to go up, and argued that money would be better spent elsewhere.

And then going back to what Rebecca has pointed out, instead, what was seen as a synergy between these two systems, ground- and space-based, and the rise of this multiwavelength astronomy that is very much dependent upon observatories in space and well-funded and well-supported observatories on the ground.

Rosson: Robert?

Smith: In 1990, the general sense was it's, as Senator Barbara Mikulski put it, a "techno–turkey," right? And cartoons of flying lemons, for example, it invades the popular culture. In *Naked Gun 2 1/2*, which some of you may remember, you can go to the Blues Bar. If you have the blues, you go in the Blues Bar, and on the wall of the Blues Bar, there are pictures of the Titanic, the Hindenburg, Michael Dukakis, and the Hubble Space Telescope because it was a cultural failure at that point, and it was an embarrassment.

And then it's utterly transformed in 1993 by the very successful Shuttle Mission and the hard work that had gone into redesigning instruments, the COSTAR, but particularly with WFPC2. The Wide Field Camera was absolutely fundamental in securing images that showed people it worked, and that, I think, helped propel it on a journey where the telescope becomes a celebrity. And it becomes a celebrity because it gets a fan base, it performs regularly, and it's got its own public image. And so, people refer to Hubble, it's not the astronomers who use Hubble, it's Hubble. It gets its own collection of merchandise. I am wearing my Pillars of Creation socks, as you pointed out, in special celebration of today. And it becomes a very different kind of instrument than any telescope has ever been before it. I mean, it's utterly revolutionary in that kind of sense.

And it's clearly a time where social media is growing. I don't think people grasped in 1990 the power of, or the coming power of, social media or even the Internet. People had not fully grasped what it would mean—some people had, I think, looking back at my notes last week. Some people like, for example, Dave Leckrone had fully grasped the potential power of the images that would be coming back, but lots of people did not think that. Some of them were still dismissive about the images, pretty pictures, why do we need to be doing this stuff? And that was, I think, transformed by the success of Hubble and the success in bringing the images forward and presenting them to the general public who could now access them much more readily than they would've been able to if it had been, say, 1983 rather than, say, 1994, 1995, 1996, and so on.

So that remaking of Hubble really, I think, is absolutely fundamental to not just the success of Hubble, but it makes a space for what becomes the Webb Telescope. If Hubble is not fixed and Hubble does not work well, there's no James Webb Telescope, at least not in the time period that proved to be the case.

Charbonneau: Yeah, that's great, and actually, I just want to reinforce Robert's point briefly, which is I do think that the public meaning instruments accrue clearly translates into political will when it comes to funding these instruments. And actually, I think one of the interesting things we can learn from Hubble—and I can give another example from across astronomy where this is the case—is that actually in times of crisis, that public attachment to instruments can be an incredibly valuable political tool when it comes to the funding of astronomy. It certainly happened in Hubble's case, right, the "techno-turkey," but then all of the Save the Hubble Telescope kind of movement, and the "the people's telescope" was a term that was thrown around a lot. But you see this across astronomy as well.

Again, just from my area of expertise in being in radio [astronomy], very close to Hubble's launch in I think 1988, the 300-foot telescope collapsed very catastrophically. And because of the crisis image of this collapsed heap of metal and wire all twisted, you had tons and tons of newspaper articles, the kind of public backlash that America had no future in radio astronomy, that we were falling behind because our flagship instruments were collapsing to the ground. This is, of course, a bit misleading because the 300-foot telescope was actually just meant to be a temporary telescope. It was only, I think, projected to be in operation for 10 years, and it ended up going for 30 years, so it way outlived its expectation. But nevertheless, it's just that, again, the public meaning of this collapsed telescope is part of what generated funding for future telescopes like the Green Bank Telescope. And so, I think that both from other areas of astronomy and the Hubble, we can really learn that sometimes crisis specifically is what can catalyze public support for instruments and directly lead to political funding for astronomy.

Rosson: I'm wondering if you guys can also help us put in context the size of this tool and the effort that was required to realize it? How big of a Big Science project was this telescope, and are there other infrastructural developments that you think are a valid comparison?

McCray: So, I think, for me at least, one useful point of comparison is a project that's being currently built in the south of France right now, which is the ITER fusion energy reactor. The salient points that I see. First of all, just the sheer political will and the personal will of the people who've been involved with this project now for many decades required to build it, with the cost now that's estimated to be going northwards of over $25 billion. But also, the fact that it's an international project. The countries that are involved with building the ITER fusion reactor represent something like half of the planet's population. It's a project on which the sun literally never sets.

I recall with some of the research that I did on it a few years ago that one of the project's main managers referred to it as globalization with hardware. That this was a way of achieving larger political goals through a large technoscientific project. And I think it's important to recall that Hubble, as well as with many other NASA projects, was an international effort and remains one. And NASA, of course, has a long history of international partnerships in both human and robotic spaceflight, as well as science missions like Hubble, JWST, and many other missions. So that international component, that I think is one of the features of so-called Big Science is something to very much keep in mind.

Smith: I think Hubble will be an example of what you might call Megascience or very Big Science. I mean, it seems to be a level above what we have traditionally seen as Big Science. It seems to be more on a par with, for example, the Large Hadron Collider in Europe in terms of the number of people involved, the size of the groups who were making observations and then writing their papers. Because I think one of the striking things about the history of Hubble is early in Hubble's history, you could see scientific papers with a small number of astronomers as authors. That changes over time, and you end up with far more astronomers involved. There's a development of a division of labor. People become specialists in areas that they would not have been specialists in before they would've worked on. For example, calibration of, say, an instrument, but that wouldn't have been their career, but that's something that develops.

Also, with very Big Science comes—you're always politically vulnerable because it's very big, and you can save a lot of money if you cancel it. And it's worth remembering that Hubble had its problems in the early '90s, at the same time as the Superconducting Super Collider is about to meet its demise in 1993, yet Hubble survived despite major problems. And so, I think it's a testament to the labor and effort that went into Hubble that it does survive.

The SSC is a good example of the kind of contingencies that can affect very large-scale missions or projects in the sense that you had the site selection where you end up with a collider in Waxahachie, Texas. At that point when the selection is made, the president is from Texas, the Speaker of the House is from Texas, but they soon go away and their political influence shifts, and we have a very different, what you might call, political economy at that point. Yet the people pushing Hubble are much more successful, I think, in maintaining their coalition. But also, I think with very Big Science certainly, one of the fundamental issues is you don't advocate once, you have to advocate continually. It's an endless effort to advocate. Otherwise, you're going to be very vulnerable politically, so. As well as the kind of scientific prizes that you can secure with these very big instruments, they come with other kinds of issues that have to be dealt with if you're going to have a successful mission or project.

Rosson: Rebecca?

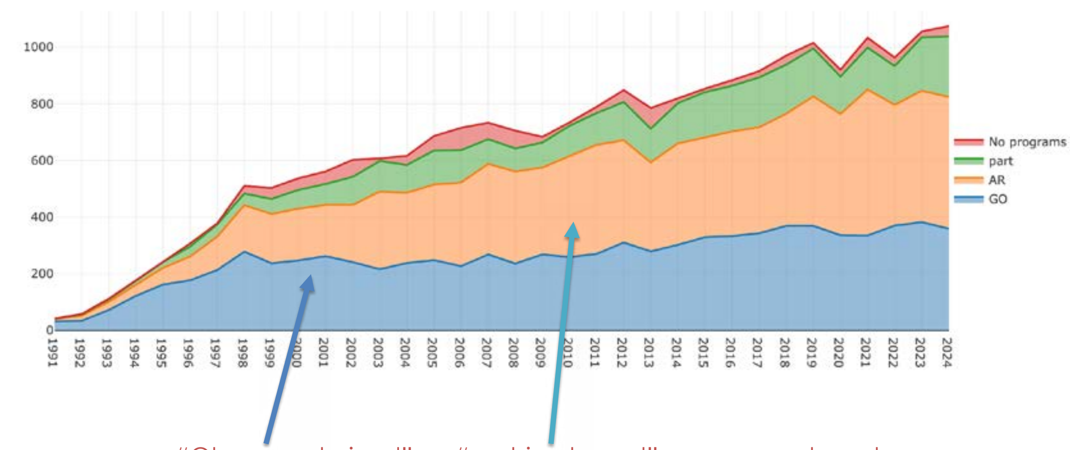
Charbonneau: We've been talking a little bit about Hubble launching during this transition point in how astronomy is done. And I think it's also very interesting, again, from that political economy perspective. Because when you think about Hubble as a Big Science project, it was first being built and developed in the latter half of the 20th century when Cold War logics were still very much at play. And so international collaboration, for example, was not just valuable in sharing the costs, but it also was politically valuable, right, in terms of coalition building. That was very important, the Cold War logics of science at the time.

And it's interesting because, in some ways, that split shortly after the launch of Hubble, in that astronomy, which has always been a global science, continued to become even more of a globalized discipline. In fact, I think there was a study by the NSF a few years ago that showed something like 80 percent of astronomy papers have coauthors from another country. People are certainly not limited to using instruments in their own countries. There was the development of Open Skies policies in a lot of observatories. But at the same time, we also learned the limits of international collaboration. There were both successes and trials in international collaboration within Hubble, but a lot of large-scale, Big Science astronomy projects that came after the fact have oftentimes struggled when they were truly born global and not owned domestically as a flagship instrument. An obvious example that comes to mind is the Square Kilometre Array that the U.S. ultimately pulled out of participating in. And so, there's an interesting history to be written about whether or not international cooperation in instruments like Hubble is as good as it gets when it comes to international collaboration in Big Science, or if there is truly a future in these born global, shared international science projects.

Charbonneau: Someone should write that book, not me, but someone should.

Rosson: I did want to also spend a little bit of time talking about data since I know that that's something that factors into many of your research for many of you. Patrick, do you want to say a little bit about how Hubble transformed data? I know you have a slide for us.

McCray: Yeah, if you're able to show it, that'd be great. So, Hubble launched in 1990, but it's important to think that just a half century earlier, the public image of the astronomer was Hubble's namesake, Edwin Hubble. Who, if you look and just google Edwin Hubble, you'll see a lone figure sitting by themself in a telescope dome, looking through an eyepiece, doing astronomy in a solitary fashion late at night. And when I first started the research that I've been doing now for the last 20 years or so, that was my very naïve impression of how astronomers did their job. That they went to the telescope alone, and they sat there and drank a cup of coffee and looked at the cosmos. And to be honest, the first visits that I made to observatories were really, really depressing to me because astronomers don't work that way. Their work looks very much like my job. They get up in the morning, they turn their computer on, they look at the data that's come in, and it's very relatable in that way.



"Observer-derived" vs. "archive-based" papers produced via Hubble Space Telescope, 1991-2024.

In 2003, the number of papers using archived data reached ~ 50% of total publications and has continued to increase.

One of the things that struck me in putting my thoughts together for this meeting was thinking back to 2003 when information managers at Space Telescope Science Institute were looking over the statistics for data usage, and they noticed something interesting. They noticed that, for the first time, the number of publications that astronomers had produced using Hubble data, for the first time, more than half of them, these refereed papers, were using archived data. And even more notable is the fact that something like 40 percent of Hubble publications had used only archived data, which is a very different way of doing astronomy. This idea that you don't need to go to the telescope anymore to collect data, that you can simply go to the archive and search through the data that's there.

And this shift in practice was not an easy one. If one looks through astronomical proceedings and conferences and things like that in the '80s and '90s, you see lots of rather agonized discussion among scientists about what it would mean if you didn't go to the observatory and collect your own data. If you went to an archive or you mined an archive for data, were you still doing astronomy or were you doing a lesser form of science? There was concern, and this is a quote from one of these papers, "that it would breed a generation of astronomers who sift through data without knowing about instruments." That they would somehow be alienated or isolated from, as Marx would say, the means of production. That they just simply wouldn't understand how their data was being produced.

And clearly, as this slide shows, that process has taken place. The process of writing publications using only data from archives or partially, that process has taken place. But the point is that there was a lot of friction to overcome in order for that to take place, both technical as well as social. That there was friction involved in archiving data for the first place to make it a public good so that the proprietary period for data was a year. Or in the case of the Hubble Deep Field, there wasn't a proprietary period, it was simply born public in the first place. But I think it's important to remember, especially for people who aren't as familiar with this history, is that there was nothing natural or inevitable about this happening. That a huge amount of effort, both technical and social, had to take place in a number of different institutions—and again, this is very much an international process—to turn astronomy, if you will, into a 21st-century form of data science, if you will.

Rosson: Would you like to respond, Robert or Rebecca?

Smith: Maybe it's worth just adding that astronomy, in terms of the public support anyway, becomes far more democratic over an extended period. Patrick mentioned Edwin Hubble. Now, Hubble had the enormous advantage of the world's large telescope to employ and having amounts of observing time that were completely impossible for an astronomer at another institution. Part of the thrust, really, of American astronomy post-World War II and also astronomy worldwide, really, post-World War II, is the availability of facilities so that an astronomer had access to very powerful instruments, and they don't have to be a member of staff of the Mount Wilson Observatory or the Hale Observatory. It's a far more, as I say, democratic process, I think. And the open access, really, of Hubble, where it's just the quality of the proposals that's going to decide if you get to observe with the telescope or not. That's a really important development, I think, in astronomy more broadly.

Charbonneau: Don't have anything to add, that's great.

Rosson: So, for our final question, I'm wondering if you guys can reflect a little bit on the bifurcated way that Hubble sometimes gets narrated. Sometimes, it's upheld as a model to emulate, and then other times, it's upheld as a cautionary tale for missions that come after it. I'm wondering if you think that there are any lessons learned that you have seen post Hubble that have been applied too hastily, or that are maybe an oversimplification of what happened, given your knowledge of the telescope?

McCray: So, I've got just two thoughts on that. I teach at a large public university, and my students, undergrads, are all in the age range of 18 to 21 for the most part. They've lived their entire lives with the Hubble Space Telescope. To them, it's just there. It's interesting when we talk in a history of science class, for example, about the history of it and how it came to be and how the history of it goes back well into the mid-20th century. So, there's that part of it, which I think is this idea of creating a cultural touchstone. And, of course, the students will ask, "Well, what's going to happen to Hubble?" which is a curious set of questions.

I think the other thing, which is going in a different direction, is to remember that Hubble is just part of a larger system for doing science. And as we know, these systems are international, they're expensive to maintain, and they're fragile. And just as we've talked about the political, social, and financial will required to create these systems, we can also think about the processes through which these systems are degraded, eroded, and change over time.

Rebecca talked about the collapse of a 300-foot—meter or foot?

Charbonneau: Foot.

McCray: Thank you—meter, sorry—300-foot radio telescope, and again, this idea of thinking about these systems of doing science as fragile entities. And I think it's important to think about how Hubble is situated within that larger and, oftentimes, precarious system for making knowledge.

Charbonneau: That's great, and jumping off that a little bit, I think that it's a great example—and we've touched on this a little bit—about how important it is to capture that public will when it comes to instruments. And the role that institutions and observatories play in actually making conscious decisions to shape that narrative and the culturally resonant images that come along with instruments. I think about that.

So, we're at NASA right now, and NASA, when it was founded in the late 1950s, was really smart about the way it was intentionally and preemptively shaping public expectation and narrative around the instruments or the missions it was creating by doing things like creating the arts program, where they have people like Norman Rockwell illustrating the astronauts getting into their suits. But also, the NASA History program getting ahead of not waiting for the history to be written after the fact but doing it as it happens. And that was enormously successful for the institution.

I did a lot of fieldwork during my graduate studies out in Moscow, so I've done a lot of Cold War astronomy history, and I went to the Museum of Cosmonautics out there, which is fantastic. But it was striking to me that as I was walking around this literal monument to Soviet space accomplishments, the people walking around the museum with me were wearing NASA meatball shirts. And I think that it really goes to show how culturally resonant and iconic these images have had, and it has a major impact. And I think that Hubble especially was really great at doing this because of the images it produced. They were not spectra or things that were very alien to the general public, but they were images of things that looked like clouds and light, things that were familiar to the general public, even if that's not quite what they were.

In addition to my background in astronomy, I have a background in art history, and so I tend to look at the Hubble images through the lens of the Romantic period. That's capital R Romantic, so this is like the 18th century, so 1700s. There was a concept that was developed by a Romantic philosopher named Edmund Burke. He's the person who coined the term the "sublime." And this refers to the idea that when we see great feats of nature like horrible hurricanes and tornadoes and large scale, it produces in us what he called pleasurable terror, this feeling of smallness that is scary, but it's also wondrous, right? And so, this is why when you look at the Romantic painters of the time, people like J.W. Turner, they are painting little, tiny boats surrounded by massive, turbulent seas that are trying to evoke this feeling of the sublime, which really taps into core human emotion.

And I think that the Hubble images, right, like the Pillars of Creation, managed to be so culturally significant because they do, they tap into that kind of Romantic sublime. And it's something that I think astronomers really have to keep in mind because a lot of the ways that astronomy is moving, we're looking at things like biosignatures, we're looking at spectral lines and atmospheres. It's hard to translate that into something that's culturally resonant to the public. But I think we have learned from Hubble and from other areas of astronomy and space history that that is very important for public support, which we are, at the end of the day, all fundamentally dependent on.

Rosson: Excellent. Robert?

Smith: Yes, Patrick and Rebecca have underlined the public links in the sense that the Hubble images present a beautiful and remarkable universe. And it's the universe that is being explored through human ingenuity. I think often with the images, there's a touch of mysticism thrown in there, which is very attractive for the public. But this whole issue of aligning your scientific objective with a publicly accessible objective, that was something, for example, that I think if we again compare Hubble with the Superconducting Super Collider now, how do you sell the Higgs boson in 30 seconds? It isn't going to work, and it didn't work. And so, the hard reality is if you cannot align your really big project with social objectives in a coherent fashion, you're going to be very challenged in order to get your project or mission to approval and then to completion.

Rosson: Great, will you please join me in giving a round of applause for our remarkable panelists? Thank you all so much; I have learned so much. I did promise a Q&A, so if you have been percolating any burning questions, we do have a microphone in the center of the auditorium. We've heard many different provocations: Is Webb the anti-Hubble, is Hubble the proto-Webb, is Hubble a cautionary tale, or one to emulate? A lot of different ways to enter this story. Oh, we've got a question from David DeVorkin.

David: Military technology?

Rosson: Ah, okay.

David: [How do you raise?] [01:13:34] certainly the size of the Hubble and large parts (inaudible) [01:13:45] to the fact of the military reconnaissance system? Do you think it's important to start?

Charbonneau: Basically, it's military reconnaissance history and how it overlaps with astronomy and Hubble specifically. So, again, not being a Hubble historian per se, I am familiar with the fact that I think it was the 2.4-meter mirror in Hubble, was in part chosen because it was already produced for the KH-11 reconnaissance satellite. It's interesting that that's the case in Hubble, but I don't think Hubble is particularly interesting in that history, in that this is the story of the history of astronomy writ large. I mean virtually every astronomical institution or observatory has been affected or shaped by military influence in some way.

One story I always like to share is, again, from my time out working in Moscow—

(break in audio) [01:14:43]

Charbonneau: —Baseline Interferometry, VLBI. It's not the most exciting name, but it's really fun to study historically. And I was particularly interested in space-based interferometers, just early space telescopes. And I was working very closely with the team who was working on RadioAstron at the time. So I was there for the RadioAstron International Scientific Council meeting, and while I was there, I was quite interested in learning more about an earlier space interferometer called KRT-10, which had launched in the '70s. It was my understanding that that was the first space-based interferometer. But weirdly, even though I could find *Pravda* announcements marking the launch of the instrument, I couldn't find any scientific publications coming from the interferometer, which is kind of weird.

And so, as I'm walking around the Astro Space Center in Moscow, I asked a number of people who had worked on the project, "What had come of KRT-10 and its scientific results?" And they all looked at me and said, "That was not an astronomy instrument." That was a cover. The instrument was pointing downwards at Earth, not outward towards the cosmos, and it was doing espionage, right, it was doing reconnaissance. I could tell you a million more stories from astronomy history, right? I'll spare you. But I think that when we focus on the connections that Hubble has with military reconnaissance, we should not see that as exceptional, but very much part of the normal—

(break in audio) [01:16:17]

Charbonneau: —history astronomical instruments.

Smith: I would just add that in a public interview, I think it was 1985, President Reagan's science advisor, George Keyworth, spoke about this issue. And he said that Hubble is new, but it draws on technologies developed for national security purposes. And that, clearly, has been underlined by some of the declassifications that have happened since then, for example, the HEXAGON program, the KH-9. And one of the great gaps in, really, our understanding of space history in general is we just don't really have access into the various companies involved. So, Lockheed and Perkin-Elmer were very important in developing reconnaissance satellites, and they're the leading contractors for the Hubble Space Telescope. But I can tell you from experience, if you want to wander around the Lockheed company in 1986 without a guide to take you even to the bathroom, it isn't going to happen.

So, there is, I think, at the heart of much space history, a lack of basic understanding of how the contractors and the companies have done things that it would be really interesting to have access to. And that's a bit broader than national security because, clearly, there are issues of proprietary data and all the rest of it, but I just wanted to mention that. I don't think it's feasible to think of writing the definitive history of the Hubble Space Telescope, for example, because there's so much stuff that we just don't have access to. So you can produce a study of the Hubble Space Telescope, but you can't produce a definitive history in an old-fashioned sense where you have access to practically everything in terms of documents and so on. It's unfortunately not going to be the case.

McCray: Just a quick thought. Robert, I don't know if you remember this, but when you and I were working on the Next Generation Space Telescope history, we were documenting and doing oral histories. I don't think either one of us interviewed Dan Goldin, at least I didn't. But I remember lots of the people that we spoke with around the project noted that he had been at TRW before coming to NASA. And there was just this vague allusion to an understanding and awareness with the administrator of deployable optics and just sort of a nudge nudge, wink wink kind of approach to that. And then wondering how that then got folded into what became the optics for JWST. And I'm sure there are people in this room who might be able to speak more authoritatively to that, but I always found that to be an interesting thread of that.

Smith: I think that raises very interesting questions about the companies and the contractors.

Rosson: Do we have any other questions from the audience?

Hammel: Hi, Heidi Hammel from AURA. I think my question is for U.S. historians. I'd be interested for you to speculate why the Hubble images were so successful in capturing the sublime? Because, of course, most other telescopes were also developing digital imaging, and they had access to the Internet, and so. And I'm asking this in the context of what lessons could there be for our other telescopes that are in flight or in the future?

Charbonneau: I'll start since I raised that. No, it's a great question, and I think the reason that they were so successful in capturing the sublime was twofold. One, I think it's just the familiarity of what people were looking at, right, in that. Robert was like, what does a Higgs boson look like? Hard to say. Even thinking about David Charbonneau, no relation by the way—David Charbonneau's work in capturing images of certain molecules or elements in exoplanetary atmospheres, what does oxygen look like? It's hard to say. But we know what a cloud looks like, we know what plumes of dust look like, right? And so, in some ways, there was more familiarity in a lot of the Hubble images, especially when you think about the very, very popular ones.

And then I think, largely, it was also the scale. Hubble images are particularly excellent at making you feel very, very small because, I mean, look at the Deep Field image, right, and try to imagine what hundreds or thousands of galaxies look like. It taps into that pleasurable terror, right? It's both incredible and wondrous, but also kind of scary. It makes you feel very small and insignificant.

So, Hubble was particularly excellent, I think, because of those two reasons, but there are other missions or instruments that have managed to capture the same thing. One that comes to mind off the top of my head is the Pale Blue Dot image from the Voyager probe, the tiny, tiny mark dot of Earth in a plume of dust as the instrument is flying away from Earth, again, evoking that sense of smallness.

And I think that going back to the success of multiwavelength, multimessenger astronomy is a way that we can perhaps capture this moving forward. So, radio astronomy really benefited from Hubble because radio astronomy, historically, does not produce the most exciting images. Actually, we're necessarily looking at the invisible universe. But for example, with Hercules A, by superimposing radio data over optical imagery, we're able to create images, right? Those gigantic radio jets that evoke, again, that same sense of familiarity and scale that you don't necessarily get across all of the wavelengths. And so, I think cooperation across different messengers and wavelengths is one way that astronomers have been very successful at evoking that sense.

McCray: Not to be overly reductionist about it, but I think it's also important to remember that NASA has an incredibly efficient and capable public relations office. It's very good at getting those images onto episodes of *Star Trek* or—I mean, we all passed the gift shop when we came into the building. Those are things that repeating that process over and over help place those images in the public consciousness, before the public eye. But then also speaks to NASA's long history in using both the Manned Spaceflight program, using the Apollo program, using its scientific missions, and developing the skills and ability to use those to accomplish a number of other goals of the agency and for the science community in general.

Charbonneau: Just to jump in, also, I think you made a great point working with public relations but also working with artists. Astronomer skills, astrophysics skills don't necessarily translate into creative or artistic pursuits; sometimes they do, but not always. And so, I think just working with artists and other professionals to help translate data into things that are resonant with the public, and recognizing where the end of your expertise is and where bringing in people from different disciplines can help. And recognizing also the specific choices that can be made. That's something that's super interesting when you look at the history of space-based or astronomical imagery is there are choices that go into what color do we use to represent methane, for example, right? And you can be very strategic about those choices in a way that don't just capture the data but translate it to a larger audience.

Smith: I would just add that there's a wonderful book on this topic by Elizabeth Kessler—

Charbonneau: I was going to mention, yeah.

Smith: —that really lays out what Rebecca was talking about, how the images, in a way, get shaped. I would also add that there developed, I think, a very effective group of people who interpret the images or carry the messages of these really large facilities and make them intelligible to broad audiences. I won't embarrass people in the room by mentioning names, but they're really good at this.

And one of the things I did when I was doing some research comparing the SSC with Hubble and the formation of the early stages of Webb was to look at how people argued in favor of the SSC. And it's a difference between night and day in terms of the quality of the interpreters, the kind of message that people have. And so, it's a very skilled job to carry that off successfully, and I think that Hubble and Webb have really benefited from the skills of these people. And people don't normally think about this with these large projects, but they're absolutely fundamental. Now, they've got things to work with, but if you can't explain what's going on in a fashion that's going to be engaging for the public, then it's a different business.

Rosson: Yeah, yeah, so we have about 15 minutes left. Why don't we take two questions at once. And then we can give our panelists a chance to respond to whichever they would like to?

Audience Member 1: Okay, so I just wanted to pick up on this theme a little bit because you already mentioned that it was a very big shift to go from the paradigm where the only people who had access to the telescopes were people who worked for a certain observatory. And now, you have an observatory where anybody can apply to use the telescope. And now with Hubble and now beyond Hubble, we have this paradigm where the data itself is available to people around the world. Not just our partners on the mission, but anybody can apply to use the telescope. Anybody can go to the archive, get the data, publish, and everybody expects to be seeing the images from the Hubble Telescope freely. And that was, I think, a paradigm largely started by Ed Weiler, who insisted that a substantial fraction of the mission budget be put toward public engagement, public outreach, public release of these images.

So, I'd like to know a little bit more about how you think this openness both toward the scientific use of the facility, but also the openness of letting people even in nations around the world who haven't been paying partners on the observatory, but allowing people around the world to take pride and be a part of the observatory. How that has affected science? Is there any downside to this, or is it a wonderful shift in viewpoint of being possessive of this information versus being open with it?

Rosson: Excellent, that's a fabulous question. I thought I saw a hand in the back too—did I? Was there one more question? Ah, yes, please.

Nina: Hi, I have a question that feeds off of that as well because I was really interested in what you're talking about with data sharing and all of that and public accessibility, not just for the American public, but also international public. And I was wondering, has that had any effect on national funding of Hubble and other projects and the fact that these images are accessible everywhere? So feeding off of that question.

Rosson: Great, thank you, Nina. Okay, so we had one question on your thoughts about international openness and accessibility. Patrick?

McCray: Yeah, I'll try to answer both questions with a nonanswer. So shameless plug, this book that I wrote quite some time ago called *Giant Telescopes*, one of its fundamental ideas is this idea of the tension between, at least in the United States, public versus private observatories and who has access to it. And as Robert rightly pointed out, people like Edwin Hubble were blessed with an enormous amount of telescope observing time that their counterparts at many other institutions didn't have. And one of the peculiarities of the U.S., ground-based astronomy system is this long-standing tension between what some have called the haves and the have-nots, between who has access and who doesn't. Which in some ways, Robert mentioned political economy, the idea of how resources are allocated through political processes, but there's also a different side of that, which is the moral economy, which are the norms and expectations about how one behaves as a member of a community. So, do you share your data, what is made accessible to other people, how are those norms put into place?

And, of course, we can look at the U.S. example, which I believe is what the question was oriented to, but compare it to the European system for doing astronomy, which is much more centralized. And as we're seeing now with debates over whether or not and how to build the next generation of Thirty-Meter class telescopes on the ground, those tensions are being played out.

Going back to the other question about data sharing and the national versus the international aspect of that, there was, several years ago, an initiative called the National Virtual Observatory, which again was this idea of data sharing, and data archiving, and things like that. But I think the idea that I find interesting is the international accessibility of the data, the fact that it is publicly accessible. The fact that people, regardless of their institutional affiliation, can apply for Hubble observing time, they're certainly not guaranteed to get it, but they can apply. But I think it also points to something that's special about astronomical data. I'm remembering a comment that a data scientist named James Gray made back in 2007, where he referred to astronomical data as perfectly worthless. And by that, he meant that it was not connected to any commercial applications, it very rarely had national security implications. But for data scientists, it was the perfect object to work with because it existed outside of these places where politics and commerce intervene. So that for data scientists, it was very much a great model object to work with.

Charbonneau: I have two ways, I think, that I can answer both questions. So, the first one is, it's interesting that we're talking about potential perils of openness, because when I think about the openness of data and astronomy, it's starting to look to me a little bit of like a Gaussian, right? We started with privately funded observatories, like the lighthouses on the hill, which were very restricted to people who had money and access. Then you have, in the Cold War period, a huge emphasis on Open Skies, international collaboration, the space sciences, particularly as a point at which nations could come together and work together. But I think that that's actually starting to change a little bit around the time of Hubble and continuing into the present.

So, for example, like I mentioned earlier, the SKA, which critically did not have Open Skies. It was a pay-to-play model in that if you were a country that was paying into the SKA and helping to contribute to building the instrument, you had priority access to that data. And this is part of the reason the U.S. ultimately pulled out of the project and focused instead on building its own comparable observatory, the ngVLA. But also, you are starting to see the decline of Open Skies policies in observatories in the United States now, see, in part because of fear of oversubscription from Chinese scientists, for example. I know the VLBA is an example of a telescope that was perceived as having too much observing time from Chinese citizens and so putting caps on the access to that. So, I actually think we're going in the opposite direction.

And in terms of whether or not there are downsides to, say, the actual public, rather than scientific competitors, but the public's access to data, it's something to think about. But one field that actually has done a lot of thinking on this already is, it's a bit funny. But in my work in the history of radio astronomy, I've looked a lot also at the development of the Search for Extraterrestrial Intelligence or SETI. And SETI actually as a subfield of radio astronomy has done a ton of thinking on this because of concerns about what would happen after contact. And so actually astronomers like Jill Tarter pioneered in the 1980s what were known as post-detection protocols, which were like a series of steps of what would happen after a positive detection of extraterrestrial intelligence. You would have to, of course, verify, consult with the UN. I think there were 10 different steps you would take in the event of a detection.

And those are really interesting models if you look to the history of how astronomers were negotiating with how to communicate discoveries to the public. Obviously, there's a limited use case for SETI specifically, but I think that there are broader lessons to be learned for the scientific community writ large, even outside of astronomy. Because I think we learned, for example, from the COVID-19 pandemic that, sometimes, translating scientific concepts very, very quickly as they're unfolding can sometimes lead to miscommunication, missteps, and even potentially risk to the scientists themselves. And this has happened in astronomy as well, right?

Of course, I think of SETI because that's where I have some background, but with a Breakthrough Listen Candidate Signal 1, the PI astronomer on that observation faced a lot of threat from the public in terms of concerns about transparency. We're seeing a lot of skepticism and concern about transparency from scientific institutions like NASA when it comes to things like UAPs. And so there is a double-edged sword here when it comes to openness with the public. But the good news is that astronomers have been thinking about this in different subfields, and so we can turn to that early thinking as a guide as we move forward into an increasingly both open and not open environment for the science.

Rosson: Robert, do you want to weigh in?

Smith: I would just add very briefly the demonstration of soft power, and American leadership in science and technology. Those are going to be very important considerations, say for Dr. Isaacman for example, in terms of project, what kind of value can you get from a project. And so, where Dr. Isaacman is sitting, things can look differently from where somebody on the ground floor who's operating the instrument is going to be sitting. So, it's going to partly depend on what audience you're aiming at, I think.

Rosson: Thank you, guys, so much. How about another round of applause?

Session Two

Building a Foundation for Hubble Science

Moderator

Samantha Thompson, National Air and Space Museum

Panelists

Lennard Fisk, Former NASA
Patrick Crouse, NASA
Marc Postman, STScI
John Grunsfeld, Former NASA

Thompson: Welcome, everyone, back from lunch. I think this will be a lively post-lunch conversation, so I can't wait. My name is Samantha Thompson. I am a curator at the Smithsonian's National Air and Space Museum. I am responsible for the astronomy collection, which means I have a lot of Hubble artifacts that David DeVorkin collected over several decades and more Hubble things that we continue to collect. And we are extending that into all of the—David got to collect all of the Great Observatories, and I get to take on all the successors of JWST and, hopefully, Roman at some point.

As we're thinking about my collection and what we collect and what this great panel works on is we have a lot of parts of Hubble that represent this kind of technological innovation aspect, a lot of overcoming challenges, doing things for the first time. But I think a lot of what we're going to talk about today is a lot of social innovations that happened with this program as well. It runs the gamut with a wide variety of tackling new things.

So, let me introduce our panel. First, we have Lennard Fisk here in the center. Dr. Fisk was a NASA associate administrator for the then Office of Space Science and Applications from 1987 to 1993 when Hubble was launched with a mirror with spherical aberration. From 1993 to the present, Dr. Fisk has been on the faculty of the University of Michigan and has served in many advisory roles, including the chair of Space Studies Board from 2003 to 2008. Now, we have Patrick Crouse. Dr. Crouse has been the Hubble Space Telescope operations project manager since 2010. He is also the ground system manager for the Roman Space Telescope. We have Marc Postman, is a distinguished astronomer at the Space Telescope Science Institute. He has served in numerous leadership roles at the institute and was the principal investigator of one of the initial Multi-Cycle Treasury programs with HST that explored the distribution of dark matter in galaxy clusters. We also have astronaut John Grunsfeld [joining remotely] —hi, John—as NASA's chief scientist and associate administrator for NASA's Science Mission Directorate. He was a mission specialist on five missions, three of which were to the Hubble, where he performed eight spacewalks to repair and upgrade the observatory. So, another round of applause to this incredible panel.

This group covers a wide range of time periods of Hubble's 36 years and a wide variety of aspects of it. So, I'm going to talk, maybe start with Dr. Fisk, and maybe a hard—the most challenging thing you guys may have faced, which was the aspect of spherical aberration. I'm wondering if you can talk about at what point did the team start to think that that problem was going to be solvable? If you can speak to any particular individuals, decisions, moments that transformed the mindset from a mode of crisis management to a mindset of problem solving?

Fisk: Okay, thank you. This event has, obviously, brought back flashbacks from my earlier career. And the Hubble spherical aberration was certainly a turning point in many parts of space science and NASA for that matter. Let me give you a little context though, start with this. Hubble ran into all sorts of financial problems during its development, and Hubble did what, ultimately, was the same thing that was done with James Webb. In order to justify the cost overruns and all that, that NASA had hyped the thing as being the singularly most important mission, an agency priority, the usual stuff.

And so when Hubble was launched, it was a lot of hype, much of which I was personally responsible for. I remember the sayings, things like, it's going to be like when a little boy in the front row finally gets a pair of glasses and he can see what's on the blackboard, and we can see what's in the universe and things like that. And there were a lot of congressmen and things who wanted to be seen with Hubble. They couldn't understand what Hubble was really about and the details of technology, but they understood mirrors. And they're told the mirror is the greatest mirror in the whole world, and you could see a dime in Washington from the Empire State Building in New York City. Apparently, the Earth is not curved, if you want to—so, I gave all sorts of interviews, and they're busy waxing eloquently about the mirrors and sending this to their constituents.

And so when it was launched, obviously, we got the first light and discovered we had spherical aberration. In my case, people know where they were when significant events happened in their life. I'm old enough to know where I was when Kennedy was assassinated. Well, I knew where I was when I heard there was spherical aberration. It was in my conference room when we were still over on Independence. And there are sad-faced people from Marshall, which was responsible for Hubble, came and said, "We had spherical aberration." I'm a plasma physicist, I didn't even know what it was, but I obviously figured out what it would be and how serious it was. And I said something at that meeting, which as far as I'm concerned was exactly what I should have said. I said, "We are not going to be judged by what happened, we're going to be judged by how we fix it," and that set the tone. As far as I was concerned, there was never any question about it, we were going to find a way to fix it because that was the whole virtue of Hubble. It could be serviced by the shuttle, and therefore, how do you fix it?

And I remember getting people motivated to do so took a little bit of effort, as you might imagine. There were a lot of downtrodden people feeling this. It didn't take long; people realized the opportunity there was to fix it. I remember some of the fixes. There was the toilet bowl solution; the spherical aberration is at the edge of the mirror, so you could have an annulus. The one I liked the least was an astronaut crawls down the barrel of the Hubble Space Telescope and replaces the secondary mirror. My career took a lot of damage from Hubble, it would end if an astronaut got stuck in the barrel of the Hubble Space Telescope, and so none of those were pursued.

But there were good things that happened. We did an accident review board, and Lew Allen chaired it. When they went into the—Perkin-Elmer now is Denver—it changed management—they discovered the null corrector that had a mistake in it. A technician, in the assembly of that GSE equipment, years ago, had put an extra space in this null corrector, and so the mirror was ground the wrong shape as a result. Good news from that is you knew exactly what you had to fix. And then, of course, along comes COSTAR, and COSTAR says, it could be built to the spec of fixing it, and ultimately, the fix was done in December of '93.

A great deal of grief NASA took at that point. Hubble was a national embarrassment. It was mentioned earlier in the previous session about the Leslie Nielsen movie where your Hubble is in the blues bar. And there were articles on the front pages of newspapers and about the one-point-something-billion-dollar blunder of NASA and so forth. And, of course, all those congressmen were just livid because they had been endorsed, and they were seen with this flawed thing. So, it took a while, money had to be found, people had to be mobilized, and it was done.

You asked the question whether there were any heroes, any particular individuals. NASA doesn't have heroes. NASA has management. NASA can put together teams of people and use those teams of people to actually solve major problems. There are people who claim that they were heroes of this event, but no one was a hero. The heroes were the people that worked together because that's NASA's style. Put together a management process, get the people to work on it, lead them in the right direction, and have them solve the problem, and that's what happened in this case.

Thompson: Maybe you can talk a little bit more about the debate of robotic servicing even before the mission versus shuttle servicing and the technical, budgetary, political kind of risks that were involved in that? What conversations were happening with regards to how servicing would be done?

Fisk: Now, you're leaping forward, right—

Thompson: Yeah.

Fisk: —since we're talking about when—I mean, poor Hubble, got clobbered by every shuttle accident. Columbia led to the delays and all the things we were just talking about, also Challenger, but Columbia also. Oh, Administrator O'Keefe didn't want to service it. Essentially, that was how he interpreted the accident review board for Columbia. The station is in a different orbit than Hubble. The station was put in an orbit that could be served by Baikonur, and Hubble is in, I think, a larger, angular orbit, and so if you went to Hubble and you had trouble, you can't go to the station and save yourself. And so that was the decision, and it was very controversial at the time.

Senator Mikulski, who was the great benefactor of all of—the Space Telescope Institute, and the Hubble, and all those things, took considerable exception to the idea that there was going to be no servicing mission. And so I, at that point, was chair of the Space Studies Board, and I was directed by Mikulski, in fact, to put together a panel committee for the board to evaluate. O'Keefe wanted to do robotic servicing, there was no robotic servicing, it had never been done before, and evaluate his plans for doing so. And so, I put what I'd call a Everybody Committee together, a committee with so many powerful people that it was not going to be able to ignore it. We had a Nobel Prize winner, we had an ex-administrator, we had center directors, we had everybody who knew anything about the shuttle. And they wrote a report that says robotic servicing is not reasonable, and there's no reason not to fly the shuttle there. That ultimately happened.

But I think what it tells you is Hubble has lived a charmed life in some sense and a life that is always impacted by some external event, in some cases very seriously. And so, you say it's the perseverance of the people, who want to see Hubble and have Hubble be successful, that has overcome each one of these hurdles that have been put in front of Hubble and left us today with a that has gone on much longer than expected to go on and done so very much.

Thompson: I'm going to ask a question that might apply to all of you, but especially in these early days when you did have a lot of hurdles that were just placed, these external hurdles placed in front of Hubble. How did the team deal with morale? Were there ever situations where people thought we couldn't move forward, that you just had to deal with limitations? If you can just speak to how the teams got through those periods?

Fisk: There are different points in this. The discovery of spherical aberration sent morale into the pits. And the investigators that have been counting on this, some of them simply said, "We're not even going to calibrate our instruments, it's not worth it." And they had to be persuaded that we were going to try and fix it, and they should get what they can. Hubble was always the best UV telescope around, that hadn't changed, but the spherical aberration (inaudible) [01:52:13] invisible. There were things that they could do, but they had to be persuaded to do so.

I can't tell you where all down through the chain of a command, the Space Telescope Institute and so forth, what their initial reaction was. But all I can tell you is from the very top of the agency, and this is people like Pellerin, and Weiler, and all the people that were responsible for the Hubble in my organization, there was no question on our mind, we were going to fix it. Had to find money, where do you get the money? It cost $90 million to fix it, and those serious dollars weren't in the budget. I'm always amused because associate administrators in my day could move money around in their budget without asking anybody. I think that must be the envy of associate administrators today. And so we did that, we found money, we found people to lead the project, and we were determined to make it happen. There are people who came forward with the COSTAR and others. But I think it's very important to know that when NASA finally decides that it's actually going to do something, then it's at its best, and people got in line and actively pursued it and made it happen.

Thompson: John do you want to chime in now?

Grunsfeld: Yeah, and make some comments?

Thompson: Absolutely.

Grunsfeld: So, I think we're missing one of the most remarkable stories in the history of space science, which is that Hubble was codesigned or designed at the same time as the Space Shuttle. And as a result, it was designed to be fixed by humans, women and men, in white suits doing spacewalks. And that was really the enabling decision—I was in high school at the time or maybe even before—the enabling decision that permitted us to go and fix the spherical aberration. And virtually, everything we've done on Hubble that have given us 36 years of incredible science has been enabled by that decision to be able to repair the telescope by doing spacewalks by humans with the Space Shuttle. And so the question about robotic servicing, for instance, is an interesting one, as we work on servicing for Habitable Worlds Observatory, where we are planning on robotic servicing. Now, I take some issue with Len about whether we could've done robotic servicing on Hubble.

For morale, in 2004, when Administrator O'Keefe announced we weren't going back to Hubble, there were some real morale problems on the broader Hubble team and in the scientific community. We had been planning on a servicing mission to significantly expand Hubble science, and suddenly, we weren't going back. And the decision that a Hubble mission was too risky because we were risking crew without the ability to loiter in space at the space station, is a decision that the chief risk manager gets to make, in this case, the NASA administrator.

We did evaluate robotic servicing. Basically, I was chief scientist, and I asked the question, "Well, if we can't service Hubble with people—?" And oh, by the way, I had been tapped to do that mission, so I was disappointed. But I said, "Okay, if we can't service with people, how can we service the telescope?" And just like missions that we couldn't do after Challenger and we found a way, robotic servicing offered that promise. And I think the work we did on robotic servicing, building on all the robotic servicing we've been doing on space station, is why we're confident going forward with Habitable Worlds.

Now, fortunately, Mike Griffin looked at the robotic servicing and agreed that it was doable in principle, but not in practice. Because the schedule for the software would never meet what we would need to do given that at that time we thought Hubble's demise was 2017—sorry, 2007 due to the batteries. But related to something you may ask us about, the ground team found a way to extend Hubble's battery life. And when Mike Griffin, on Halloween of 2005, put Hubble back on the manifest, there were a lot of happy people at Goddard Space Flight Center, Space Telescope Science Institute, and around the world.

Thompson: Thank you, Marc, you want to speak to that at all?

Postman: Yeah, sure. Well, I will say that my whole career began arriving at the institute eight months before Hubble launched, so I lived through the whole depression-and-joy and depression-and-joy cycle, but mostly joy. Even after spherical aberration, I would say, almost to a tee, everyone at the institute was determined to fix it and figure out a way to fix it. And not only that, also to figure out a way to use the data that was coming down, even aberrated, and how to repair it or improve it with software. So, with image deconvolution, we developed the techniques for that. And there was some reasonably good science that came out, but nothing compared to what it was once it was actually fixed.

And I just want to say, in my mind, the greatest decision in the history of Hubble was to fix it and do it quickly. And hats off to all the people who made that decision and, in particular, to the people who literally risked their lives, one of whom is on the screen there, to actually go do that, so.

Thompson: Actually now, that we're talking about risking your life, John, do you want to talk a little bit about the practical challenges, the risks involved in servicing the Hubble Space Telescope? It really did increase the longevity of the mission, but if you can speak to the practical nature of what that meant?

Grunsfeld: One of the exciting things about being an astronaut and working on Hubble is that each time we did go to service the telescope, we reinvented the telescope. We could've abandoned Hubble and built another Hubble, and maybe it would have been 15 or 20 years before we would've gotten a new telescope rather than 1993 after the first servicing mission. I think once you decide to be an astronaut, you're accepting of the risk that something goes wrong and you don't survive. For me as an astronomer, astrophysicist, going up to Hubble is like the Holy Grail. So each time I went to Hubble, there was really no internal or even with my family because they know how I feel, discussion about whether it's worth the risk. Hubble is so fantastic. It's made so many contributions to science and to the world that I viewed it was worth the risk.

In fact, when the Space Studies Board was doing the Hubble Servicing Study before Servicing Mission 4 was put back on, a group of astronauts, active astronauts led by the chief of the Astronaut Office actually signed a letter saying that we felt like going back to Hubble was worth the risk, and so there wasn't any question there.

I will say that I was selected as an astronaut in '92, and so I got to participate in some of the prep work for that first servicing mission. And it was a very exciting time down at Johnson Space Center and all of our partners because we knew we could fix it. The engineers came up with the technology. We did some preparation on a previous shuttle flight to practice the kind of EVAs, spacewalks, extravehicular activity, that we would need to do for Hubble. There was still some uncertainty about whether all of the technology would work, but it was very much a lean into it kind of activity. And all of the resources of human spaceflight were put towards making sure Hubble was successful. In part because Dan Goldin, the NASA administrator, had made it clear that we needed to be successful on Hubble or all the rest of our plans with the space station and all the spacewalks we would have to do were in jeopardy. And so, Hubble really was a mission where the agency hung in the balance.

Thompson: Thank you. I want to think a little bit bigger about what servicing Hubble meant for missions at NASA, and I'm wondering for Hubble itself or if you have any preset concept of what it meant for other missions. Basically, what experience we had with servicing, how did that change NASA management's approach to sustainability of missions, to serviceability, to how we would maintain telescopes once in space?

Grunsfeld: I'll make some comments about the International Space Station. We had been designing Space Station Freedom, which then became the International Space Station. And while we had looked at a lot of different studies for how to do spacewalks to service the space station, which is removing failed components, adding components, even the assembly itself, we hadn't really addressed the fact that we didn't know how to do most of those things. The impetus to service Hubble on the first servicing mission really highlighted all the things we didn't know and proved out a lot of techniques that we then used on every other shuttle mission that had spacewalks, including all of the space station assembly missions. And some of it came down to tools. For instance, we developed a power tool, the Pistol Grip Tool for Hubble, that we've used on virtually every other spacewalk since.

Thompson: Amazing, I want to switch a little bit. So, we talked about servicing missions as a way of elongating the life of Hubble, but I want to talk a little bit about that with you with some of the on-groundwork to make that happen as well. So, I'm hoping you can discuss some of the operations and engineering—how operations and engineering teams have managed aging systems of the telescope?

Crouse: Yeah, I was going to say, maybe one of the downsides of the notion you're going to be servicing regularly is I think people didn't think they had to worry about how systems are going to age. They just knew that they would have a servicing mission, and they would replace it. So when in the late '90s they had a series of failures of the gyroscopes, and they were actually sitting without enough gyroscopes to do science, but they had another servicing mission coming, that really spurred the team to think about how do you start looking forward. People before me created a strategic process to look at life extension initiatives. But importantly back then, they looked at, okay, we know that gyroscopes and the way that they're built and the corrosive fluid that the very thin wires have to run through, that there's a failure mechanism there. And so, they looked at can we do operations with less than three gyros. They started the development of a two-gyro control law with the idea that it could go down to a one-gyro control law.

And so then when the Columbia accident occurred and they realized that either a mission may not come or it may be greatly delayed, they made the decisions to move into two-gyro mode to help extend that mission. As SM4 was put on the books, we were fortunately able to also get, in a very short period of time, running one gyro science, and that's a good thing. We've been running one gyro science since 2024, and we're being very productive and very proud of that performance.

Postman: Yeah, and I can add from the science operations side, the thing that we've often done is both to make sure the instruments can last a lot longer. So, for example on COS, we periodically shift where the geocoronal Lyman-Alpha line hits the detector, which causes damage, and that allows people to continue to use that COS detector for many more years than it would otherwise be usable. There were a whole bunch of other things we did by inventing new ways to use instruments, new modes. Just 10 years ago in 2017, but that's 20 years after STIS was installed, we implemented a new mode on STIS using the BAR5 coronagraph, which gave Hubble the ability to do high-contrast imaging with a contrast ratio of a million, which is something that I don't think anyone initially thought Hubble would be able to do. So, by continually inventing new modes, making sure the instruments work well by doing what you can from the ground by changing their configuration, you allow even aging instruments to really remain viable and do state-of-the-art science.

Thompson: I'm wondering, and this is a little bit how you continue to work with Hubble as it continues to work and age at the same time, but also how you think about future telescopes like Roman. Are there lessons learned in how you think about how you maintain a telescope for longer than the mission timeline? Are there lessons learned that you think you can integrate either both in Hubble or in other observatories?

Crouse: Yeah, well, I think we're used to NASA. There's many satellites that have lived well beyond their original design lifetimes, and certainly, there were other missions that also developed, reduced our modes of operation. Maybe they didn't have the stringent pointing requirements of Hubble, and so it takes a little special attention, a little special look at it, but recognizing, right? I often say I'm not one to think about resources of if that other satellite goes away, my satellite can take, use of those resources as a guy who's operating a satellite that's been up there 36 years. And certainly, with Roman where it's a five-year primary mission, we expect to have fuel for at least 10 years, and if we get a good ride off of the rocket, probably many more years beyond that. And so certainly when it comes up in conversations and we talk about the five-year prime mission, I always say, yeah, but we're thinking also about 10 years, 15 years, 20 years down the line because as we anticipate, there'll be new science discoveries that'll open up that we'll certainly want to take advantage of that longevity.

Thompson: Mm-hmm, maybe, Len, I can go back to you. In 1990, was that the thought process then too knowing that it was designed to be serviced? Was the team thinking about things in 10-, 15-, 20-year increments, or was it more let's get through the first mission dates?

Fisk: All right, in 1990, there was only one thought, which is how to fix it. I'm sure somewhere around the world of—we didn't even know that we had something that was going to have to be maintained until we got to that point. There is something to be said for focusing on the problem at hand, and I think that was what the team did. People that were there at the time can probably even answer that more because you remember, I see these things from the 30,000-foot level. Well, I'm the guy in charge, and I have people that report to me, and I don't know what they're doing. But I know that the effort, the first effort that had to be made was to make it work.

And John said it correctly that the Hubble—first of all, you remember in this era, all missions were launched on the shuttle, so there were no ELVs at this time that were being used. When the Challenger accident happened, things were just stacked up, and they had to work it off. I made a lot of trips to the Cape at that point working through the inventory of missions. But the shuttle was such a central part of NASA at that point; it was going to be the only launch vehicle. They had some illusions at that time it was going to be like an airline. We were going to launch every two weeks or something silly like that, and of course, that all ended when they killed the schoolteacher, Christa McAuliffe, and so.

So, the whole philosophy with the Shuttle became, it was (inaudible) [02:12:19], and ELVs came back after that time too. But there were a lot of missions that were all designed, they could only be launched on the Shuttle. They got returned to the hangar when the Shuttle was being repaired and to re-fly again, and then we would fly again. But the Shuttle program, at that point, in NASA was the program, and one of its virtues, as far as Hubble was concerned and other missions that we had, was that you could, in fact, service things, and that that should be in your planning process. First step is to have a mission worth serving, and that occupied the time between 1990 and 1993.

Thompson: Nice.

Crouse: I will just add quickly. When I came to Hubble in 2010, there was conversations about our goals are 2015, 2016, get the mission to there, and the folks on the team were saying that we're trying to get to 2016. I just came from missions that ran much longer than that, and I thought, no, the mission, because people would talk about the mission being back when they're doing the servicing missions. And I said, well, no, the mission now is to operate this satellite for as long as possible and returning the most science that we can. And I met with Matt Mountain at one time back in those early days, and we talked about creating a 2020 vision to make sure that we were looking further ahead and always trying to keep our eye on the horizon, and luckily, we've been able to [use?] [02:14:06] the bar a few times.

Grunsfeld: Well, when we serviced the telescope in 2009, we gave a five-year warranty, labor included. But I think Pat is being very understated that the team at both Space Telescope Science Institute and the Goddard Space Flight Center have just done Herculean things with keeping Hubble operating. And if you had asked me at wheel stop on Atlantis in 2009, will Hubble be operating in 2026, I would've given it slim odds. But the team has just done fantastic things in software and protecting the hardware such that we still have a telescope that, for all practical purposes, is still as fully capable as it was when we left it in 2009.

Thompson: Yeah, that's fantastic. I want to talk, maybe, about some of the programmatic innovations that helped Hubble maintain its element as a premier science facility. So, maybe this is a question for you, to talk a little bit about allocating observing time, data collecting, and dissemination, things like that.

Postman: Yeah, I think. First of all, the first panel did a great job in demonstrating the power of the data archive for extending scientific legacy. I think one of the innovations that helped make that a reality is not only putting the data in a public archive, but also a combination of the NASA funding that goes to help with the research, and having the innovative tools and archive interfaces that allow you to find the data and in real time, explore the archive. So that you can find what you're looking for, you can do quick analyses to see if this is—and this is something that we are continuing to do and which, I would say, the scientific success of Roman is going to depend very critically on that same kind of archival capability because it really is mainly a survey archive instrument. So that's one aspect of things.

The other in terms of telescope time allocations, obviously, community-led decisions on that, having the peer reviews are an important thing. That's not new; even the ground-based communities did that. But what I think we innovated a bit with at the institute is different ways other than GO time, right? And so, we came up with the Multi-Cycle Treasury programs, long-term things which enabled science that you wouldn't be able to do with the GO call because you never get that much time. Or the Snapshot Survey program to allow people to do lots of targets, and maybe you get some of them and not all of them, but at least, you can propose that kind of thing. Or now, what we're doing both with Hubble and Webb is very rapid targets of opportunity, proposals which allow you to look at things that explode, or collide, or do whatever, and you can do these very rapid returns. I also remember when the comet or the asteroid hit Jupiter. That was another very exciting thing where we hadn't planned on that, but obviously, it happened, and the response to that was great, and Hubble images of that were amazing. So, it's just having that flexibility to rethink how you allocate time.

The other aspect of this, too, and this goes to instrument aging, is I think when we realized NICMOS was going to lose one of its cold channels, we allocated a campaign where we said, "Okay, we're giving priority to this instrument at the expense of some of the others for a short amount of time to make sure we maximize the science from that." And so, all of those things really help make sure we're getting the maximum science out of Hubble.

One final thing I just would add is we also want to make sure we maximize the science we get out of the many minds that are in the community. And one of the ways we've done that is to implement dual-anonymous review, which allows PIs who maybe never would've gotten time to now get time. We have, even with Hubble and with Webb, I think something like 30 percent of the PIs that get time each year, had never before been a PI on the instrument. So, it's really bringing in new members of the community to do great science, and so all of those things really help.

Thompson: Amazing. Between servicing missions and work done on the ground to increase the longevity of the telescope, I'm wondering, does management see those types of things as a reason to continuously invest in Hubble? Is that part of the mindset that you've proven you can keep a telescope operating? Just thinking about what goes into that question of how much are you putting into the telescope now to keep it living beyond knowing all the work that has been done to maintain it over time?

Crouse: So, we work in the mindset that we're trying to maximize the science now while also not limiting the lifetime of the telescope. And for much of the time I've been at Hubble, we've been fortunate enough that we've been able to do both at the same time. We've been able to go out to the community, get their proposals, and assess what they need to do the science that they're proposing to do, and really support that community. We've made some reductions here recently, but we've been able to make those trades to both look into the future to keep the observatory running while not necessarily impacting science and also thinking about integrating over the longtime curve, right? We can make some enhancements now while we have expertise around who know the telescope, know the instruments, know the software, can make the changes. We'll get that return on investment later. And so that's always been a guiding principle, since the time I've been here.

And we've done another one of those recently when, in 2021, we had a failure on our Science Instrument Command and Data Handling system, a critical instrument for being able to send commands to the science instruments, and retrieve that data, and get it back to the ground.

Fortunately, it's a redundant system, [science?] [02:21:16]. Servicing Mission 4 had replaced a unit as part of that, and so… I guess the good news I'm trying to get around to recording is that we've been working on an implementation that we think will restore that redundancy that we lost. So we were able to successfully move over—I should tell that part of the story, too, I guess. We were able to successfully move over to the redundant side in 2021, and operations have been fine on the other side ever since. But we've been looking at what does the future hold and can we continue to offer it to the observatory, and so we've been working on restoring that redundancy.

It's a very complex path. It involves essentially everybody on the team, the science planners at the institute, and the software the institute builds, the flight software for both the spacecraft and the instrument, and the payload on the observatory. It's been a long, arduous path to come up with the ops concept, develop the requirements, and do that development, but this week, we completed half of the final steps. We did what we call an operations acceptance test for the installation on the spacecraft, the 486 computer flight software. We went through that installation this week, and we'll formally install it on the 16th of June. And then following that, a few weeks later, we'll do the test and installation as well for the payload software. And so again, hopefully, that's a system we will never have to use, but having that system, I think, gives us a certain amount of insurance as we look forward to being able to provide operations into the 2030s.

Thompson: Amazing, I think you've all spoken to various ways that the program has adapted. I was a little inspired, John, by your story about servicing mission during Christmas where you're trying to get back before Y2K hit. And so just wondering, just a fun moment, if you could all maybe talk about something that you think that you adapted to really well within the program, something that maybe doesn't get as much—like a part of the spherical aberration, just maybe your favorite memory from overcoming a challenge in the program?

Fisk: In my case, of course, it's overcoming, the fix. There, I think that one of the things that I learned when I was associate administrator with missions, just in general, it's an interesting comment, it's always the low-tech stuff that hurt you. The Hubble, the mirrors were low tech; I mean, there was nothing exotic about it. Fine guidance sensors and all that stuff, that was the high stuff, that got the attention. I had many missions that if you say, where was the failure mode, it could've been workmanship, it could've been other things.

Some years ago, somebody asked me, GAO or one of organizations called me up and said what did I think of the risk management plan for James Webb? I said, "I have no idea, I mean, it had nothing to do with me," and they said, "Oh, we want a comment from you." And I said, "Well, every risk management plan I ever saw for a mission didn't take into account the risk of the low-tech stuff, was the morale of the workforce right, were they incentivized, and all these things. That's the thing that always catches you. I don't know how you deal with it, I don't know how you keep it away, but that's the risk." And that was a risk with Hubble, it was a risk with Magellan for me, it was a risk for other programs that I had. I think when we learn these lessons, we're not necessarily looking for the right thing when we're trying to do a risk management plan because that's the hidden stuff that could well hurt you.

Thompson: Marc, want to take a stab?

Postman: I don't know if I can speak to a specific thing, but I can give you a personal highlight for me or a moment of great ecstasy with Hubble, which was when we saw the M100 comparison before and after. And I remember the reason, well, of course, this was the definitive demonstration that the fix, COSTAR and WFPC2, worked, and the telescope was going to achieve its full potential then. But for me, the reason I remember this so vividly is not only the stress and the disappointment we all went through when we found out the flaw. But my second daughter was born in November '93, and I remember in December of '93 being up at 2:00 a.m., holding her in my arms, watching NASA TV and watching the repair mission. And then a month later at the AAS, seeing that image was just fabulous. And then that's when I knew that NASA could do anything. If they could do this, I'm sure we can do Habitable Worlds Observatory.

Grunsfeld: I think from my perspective, following on Marc's comments that Hubble has a history of doing the impossible. And for me personally, I was challenged with trying to repair the S-Band Single Access Transceiver, which was this little box that was never intended to be serviced. It was put in there with features that made it not amenable to astronauts in big, bulky gloves. I imagine that the first servicing crew felt like there were things that would be really hard, but we have all these review panels for Hubble have over time. And I had the pleasure of repairing that little box, the SSAT, and then later, the Power Control Unit, the trainer for which is in the Air and Space Museum, so you can see that, And then later, the Advanced Camera for Surveys. All of which review panels said, "Don't try and repair them, it's impossible."

The amount of blood, sweat, and tears we put into coming up with fixes as a team. As Len said, the team comes together and we figure out tools to build and low-tech stuff, a newer wrench, or just training the heck out of taking connectors off every single night for a year to practice for the Power Control Unit. Overcoming those hurdles, I think, is the story of Hubble over time. That we've kept the observatory alive to enable the science by a series of things that people said were impossible and for me, personally, brought me great joy.

I remember coming back from the 2009 mission at the press conference, and after repairing the ACS, I said, "That's the happiest I've ever been in my life." And suddenly, I had a moment of panic because I looked in the audience, and there was my wife. I corrected myself saying, "The fourth happiest moment, marrying her and the birth of each of our children, and then repairing the Advanced Camera for Surveys."

Crouse: In October of 2018, I had just been meeting with headquarters people, keeping them informed of the health of Hubble, stability, and the outlook going forward. A number of us had already left for the day, I was 10 miles away, perhaps, and the pagers are going off that something has happened. And we get back into the control center, and the third—Service Mission 4 had replaced all six gyros, we had brand-new gyros. In 2018, the third of, what we call, the standard flex lead gyros had failed, and we said, "Okay, now, we're down to the last three."

And we turned on a gyro that we had stored in 2011, it had been giving us a little bit of challenges in 2011, we had turned it off in favor of some others, stored it. When we turned it on, it was saturated, it was not usable. And, yeah, there was a lot of down moments right away, but then, true to the nature of the Hubble team, people rallied, said, "Okay, what can we do?" And we did simple, low-tech things, can we rock the spacecraft to make this float move on this gyro? And we saw early signs that, yeah, this is going to work, and we're able to recover that gyro, and so there's a lot of joy. And then we managed that gyro for the next six years until 2024, we decided it's time to move on, but that was a big moment in 2018.

Thompson: Amazing, well, thank you, give a round of applause, thank you all so much. We do have time for questions. So we can do the same thing if people want to line up there. I can go to David DeVorkin first, though. David?

David: Well, let's start with the question about the options that you faced for the servicing. I recall that one option considered was to bring the mirror back or bring the whole telescope back. How serious was that?

Fisk: It couldn't have been serious because the shuttle would have to pick it up, and the Hubble was too heavy to land in the shuttle bay. In fact, one of the joys of the launch of Hubble was there's an abort site in Africa for the shuttle. If we hadn't gone to orbit, the Hubble would have to have been jettisoned off the site, it couldn't land in that abort site. So fortunately, none of that happened, but I don't see it coming—I think the only way it's going to come back is on somebody's head probably someday.

Thompson: Let me go to another question.

Crooke: Hi, Julie Crooke, NASA Headquarters. So, I have a question for you guys, but first, I want to give a little context. So, I'm a Hubble Hugger, a James Webb Hugger, a Roman Hugger, and a future HWO Hugger. So, I love flagships, and, actually, I did work on the first Hubble servicing mission. I was one of those optical systems lab rats that was handed the Wide Field Planetary Camera spare and said, "Go measure the wavefront error, make sure the wavefront error is not in the instrument," and making sure it was in the actual telescope. So anyway, my question is given—I also understand the context that we have to give a definitive, limited, lifetime, first primary science, blah, blah, blah, has to happen with five years. And we want this, we spend billions of dollars on these beautiful flagships, however, given that context, the fact that we only plan to fund the first primary mission. And then in future years, when they continue to last decade after decade, it's taken out of the astrophysics division's budget or, well, Congress. Congress does also, say, fund this much for each of the flagships, but in the spirit of making sure that these flagships are fully utilized to the extent possible, and Hubble is the best example ever because of how long it's lived and it continues to thrive, thanks to everybody who worked on it.

My question is, how do we ensure that—you know? Is there a way to ask Congress or NASA to make sure we balloon—continue to have funding for the science operations way far ahead? Of course, if it's warranted, it has to go through the Science Senior Review, etc., things like that, but it feels like sometimes we're contemplating trading Peter for Paul, this flagship versus that flagship. And how do we make room for the next flagship when we're funding all these other flagships, and I want them all to continue to exist and thrive? So that's my question. I'd love to hear your thoughts on that.

Fisk: Well, you are singing the correct tune there. This is a problem for all of NASA; it's not just astrophysics. I mean, imagine if you were a Voyager investigator, the prime mission was to stop at Saturn, it's been going on for another 40 years. But if you said, what's the cost of this mission going to be, you need a definitive end for the costing of it. Because when you sell a mission, when you have its launch plus 30 days as a mark, and then they go into Phase E if they're still using the same nomenclature. When you tell Congress, or OMB, or whatever it is, you have to give it a finite number. And it is a problem throughout, at least it was in my time, and I assume it is still today, that some of these missions last a very long time, and they're very productive. And there's an MO&DA or whatever—well, I used to call it, budget—that has to cover these things, and the agency has to provide the funds for that. Flagship missions are different; they actually get their own line for a long time.

But I don't see an answer to it because, first of all, Congress appropriates two-year money, so any money you get from NASA, it has to be spent within two years. They don't fund the entire mission at any point. That's not the way the system works.

Grunsfeld: Yeah, I think, Julie, you're bringing up a really important point, and I had to address this when I was associate administrator, as Len did in his time. I think a lot of it is about setting expectations when we go to Congress to get a program approved and then also communication. Hubble had a lifetime assessed at 15 years, and I don't think when it was sold, anybody said, "Hey, we want to make sure it has funding for 36 years." But Hubble has proven that with the right care and feeding, these Great Observatories can last a long time, as has Chandra, and Spitzer, and Compton before that.

I think a lot of it is a communication question, and when we go to talk about Habitable Worlds in Congress, we should come up with a number that is a nominal lifetime, which is an engineering lifetime. But I think we should communicate with Congress a science lifetime. I know, Julie, you're an advocate for robotic servicing, and that we say the search for an Earth 2.0 around a sun-like star has a very uncertain outcome. It's discovery science, and we're searching this grand question of, are we alone in the universe? We want to give Habitable Worlds a decent chance at finding it, but given our ability to keep the observatory operating for a long time, we just want to let you know up front that we will be requesting mission-extension funds as long as the observatory is providing world-class science. So, I think part of it's an expectation and communication issue.

Thompson: All right, we can do next question.

Audience Member 2: This isn't a question, but a comment. I want to compliment the Space Telescope Science Institute by having their parts work together, and then in particular, scientists can work with operations people. And I'm thinking—and Marc, you can correct me on this—that Adam Riess had an idea of how to get a better estimate without wiping out fixed pattern noise by moving the targets, and then you get a thousand measurements instead of just one. And that led to a Nobel Prize measurement, and Marc could correct me if I'm wrong, so—

Postman: No, that's right, that's the spatial scanning mode.

Audience Member 2: Okay, and I haven't heard of that ever happening before. That the operations people are down in the basement and the scientists are way up here, and they don't ever talk, but evidently, they do at the institute. And I just have my memory of the recovery that the GHRS, Goddard High Resolution Spectrograph, was the last to be exercised after the repair mission. My postdoc and I drove up to the Space Telescope Institute on Easter morning, and we came and we saw this beautiful spectrum. GHRS was fixed, but it was Easter morning.

Postman: Spectrograph was resurrected. No, I think that's a key thing, and that also relates to your comment of teams. The way these things succeed is you put away your career label, and you just work together with who you need to work with, and then whether you're a scientist, an engineer, a software developer, an administrator, it takes all of us. As someone once told me, the science is a necessary but not sufficient condition for mission success, and so that means you need the community, you need the space agencies, you need the government, you need your colleagues, and it takes all of those to make it work, and the astronauts, of course.

Thompson: Question.

Audience Member 3: I just actually wanted to add another comment of gratefulness. It was mentioned earlier that servicing missions actually create, refresh, and, in some sense, make a new observatory every time we did the servicing mission. And that has enabled fantastic, new scientific discovery, so, all the servicing missions have created a new capability for Hubble. This last one, SM4 that was done in 2009, has enabled us, with Hubble, to make fantastic advances in science. And I think about things like looking at these interstellar objects coming through the solar system that we didn't really know existed, and now, we've been studying them with Hubble.

We now have actually imaged a photo, a planet in the process of forming. It's accreting material, and we can only see it in the ultraviolet. And that was only capable because of the instruments that were installed and repaired on SM4. So, those are just a couple of examples, we have many of them. So, was it worth it to do the servicing scientifically? Absolutely. We have just done absolutely groundbreaking, breathtaking science since this last servicing mission that we could never have done before. So just hats off to everybody who made all the servicing missions happen, and it certainly has been scientifically worthwhile and continues to be. I could go on and on, but the next panel will say more about it, but thank you, yeah.

Thompson: Yeah, I'll echo scientifically valuable, historically valuable. Like you said, we've had NASA people come out. In our great collection of Hubble artifacts, we've had people come, Habitable Worlds come see WFPC2 to see how some of that works. It's nice to know they've been used as a resource to this day, and our millions of visitors really enjoy it too. So, David, I'm going to give you the last one.

David: Well, Sam, I just wanted to ask you a favor. Could you let the audience know that we are saving [Hubble artifacts in the collection at the National Air and Space Museum] [02:44:57], and they will become visible after July 1st. And what I'm asking you to do is maybe give a quick description of what people will see?

Thompson: Yeah, I can definitely do that. So, in a month, you'll be able to see back on display at the museum just down the road, the Hubble Structural Dynamic Test Vehicle, which was something built by Lockheed, to do testing. And it'll now be surrounded by the backup mirror, which my understanding was ground correctly, the COSTAR and WFPC2, if you want another one, and WFPC2. And we will also have the Faint Object Spectrograph on display. So, all ways of telling the story of Hubble, what it meant for space sciences in general, but then also the science, dark energy, black holes, all the things that it told us. So thank you for that opportunity, David, to talk about that. All right, thank you all, let's give our panel a round of applause.

Session Three

Hubble's Key Scientific Findings

Moderator

Ray Villard, Former STScI

Panelists

Jennifer Wiseman, NASA
Amber Straughn, NASA
Ken Carpenter, NASA
Julia Roman-Duval, STScI
David Leckrone, Former NASA

Villard: Well, good afternoon, all you Hubble Huggers. I know almost all of you; I've worked with you for many, many years. For those of you who don't know me, I was the Hubble News director at the Space Telescope Institute for 35 years, and I'm working on a book about that. Len Fisk talked about the trauma of spherical aberration. I had a *Toronto Star* reporter come and interview me in 1990 and said, "Ray Villard has the world's best crummy job." That's history.

So, let me do a quick intro, then I want to show our distinguished guests here. I do want to thank Brian and Lois for inviting me; I'm very flattered. I've been looking forward to this for months, and I was heartbroken when it was delayed from the fall. But when we come to the Q&A, I want to come back to the great cultural and historical context, and I'm sure most speakers will too.

But I want you to stop and think—and Dave and I have talked about this—what will they be saying about Hubble 500 years from now? We talk about Galileo in all the introductory astronomy classes. I think they will say Hubble was an audacious expression of human curiosity, and our careers have celebrated that. Astronomer Adam Frank said that Hubble is our gift to humanity of the future. We've heard about Hubble transforming astronomy, and we'll hear more about that from our distinguished guests, but I can't emphasize enough, Hubble is a civilization game changer. Hubble, there was an explosion of awareness about the universe around us, and my key point, which Dave and I have talked, there's only a first time there's a first time. Hubble is the first time, and Hubble has long lists of firsts, which my distinguished guests will get into.

So with that, let me introduce the panel. Dave Leckrone, one of my favorite Hubble Huggers, and we've been together forever. I kept this short, gang, because I want to get the show on the road. For over three decades, Dave served in various scientific leadership roles at the Hubble Space Telescope project. I was senior project scientist, and I was with Dave through all those Space Shuttle servicing missions. My favorite Dave expression was when the bolt stuck on with take two, and Dave was like, "Hmm." Great picture, Dave, anyway.

Okay, next to Dave is Ken Carpenter, Hubble operations project scientist, ground system scientist for the Roman Telescope at—Dave's been at Goddard, of course—Goddard. And now, what I found interesting, you're working on an Artemis-enabled Stellar Imager, so you're taking astronomy to the Moon, which is wonderful. It makes me excited to be thinking about doing astronomy from the Moon.

Jennifer Wiseman who's senior project scientist for Hubble, head of Goddard's Laboratory for Exoplanet and Stellar Astrophysics. Jennifer studies star-forming regions in our galaxy. The one thing that I surely enjoy, I know Jennifer especially, science policy and public science outreach, and she has done wonderful sessions at the AAAS, which just I found enthralling. So, she's great at that.

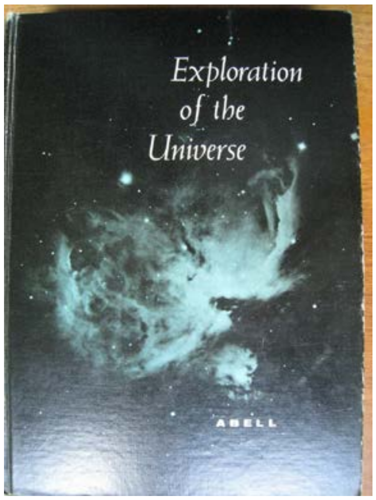
Julia Roman-Duval, our Hubble Space Telescope Mission Office. Julia's done a lot of things, I just tried to shorten it, interstellar clouds and gas properties and their influence on the formation of extra—evolution of galaxies. I was going to say extrasolar galaxies, but that's not—

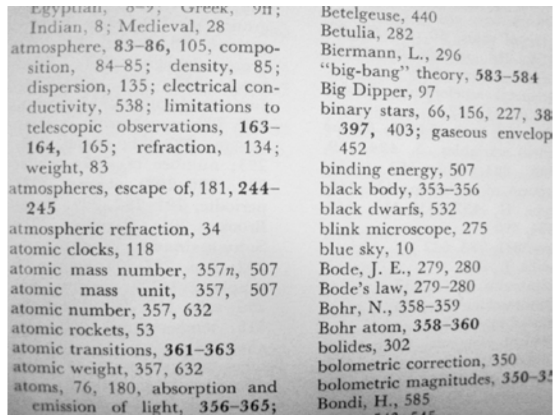
Amber Straughn, Hubble, at Goddard—of course, Julia's with us at the institute. Amber Straughn at Goddard, project scientist for Webb communications, served as associate director for Astrophysics Science Division. And her research, which she'll talk about, is areas of galaxy evolution.

"Hubble has taught us to see the properties of a universe humans have been able, for most of their history, to probe only with their thoughts. Beyond the uniformity of the naked-eye universe, there is this other universe, the one Hubble discovers with astonishing clarity. This is a place full of discordant objects, of cataclysmic disturbances. You see both energy and matter, revealed with a vibrancy that is simply overpowering. As forms, as colors, these objects are entrancing.

NYT Editorial 2004

This is from the *New York Times* editorial. I thought this really encapsulated the wonder of Hubble and its cultural impact. It says everything. I couldn't write it better myself as a Hubble spin meister. But with that—get first slide up Dave—I hope that's yours. Is that yours?





Astronomy 101 Text
Abell
Copyright 1964

Leckrone: That's right, okay.

Leckrone: Okay, and I guess that works. It's, well, obvious to say Hubble is rewriting the astronomy textbooks. And I thought it might be useful or fun to go back and look at my Astronomy 101 textbook from when I was in college. This is the *Exploration of the Universe* by George Abell, a very famous extragalactic astronomer, and I just looked in the index to see what is it—? There are things that we take for granted today as being a critical part of modern astronomy, and I find anything like that in this index from my original Astronomy 101 text. So, I went to the *b* part of the index and looked for black holes. Black holes are not mentioned in the index, hmm. Oh, I should comment, of course, that Hubble provided the first definitive detection of a supermassive black hole, in the center of a large elliptical galaxy. And that was with the Faint Object Spectrograph with STIS, which was launched, flown in 1997. We called it the Black Hole Hunter, and basically over the course of a few years there, we established—we—Hubble scientists established that supermassive black holes existed in the nuclei of almost every galaxy, if not every galaxy. And there are interesting relationships between the mass of the core part of the galaxy and the mass of the black hole, which surely has something to do with galaxy evolution.

But also, quasars are missing, there's no mention of quasars, and we know now that quasars are—or it's a phenomenon. The quasar phenomenon is associated with these supermassive black holes of the nuclei of galaxies. Basically, they get a large influx of food, and there, it gets compressed and heated up to very high temperatures and shines very brightly. And across the cosmos, astronomers back in the 1950s or so started seeing and picking these things out as quasars, and they called them quasars. But it hadn't even made the textbooks at that point. Hubble demonstrated the phenomenon that quasars originate with the supermassive black holes in the nuclei of galaxies.

So I looked in my index, there's no mention of dark energy or an accelerating universe, hmm. No mention of dark matter, which is the skeletal framework, the underlying gravitational infrastructure of the whole universe, hmm. I don't see anything about galaxy mergers or how you grow big galaxies from small galaxies, the so-called hierarchical model, hmm. And there's nothing about exoplanets, for heaven's sakes, and particularly exoplanet atmospheres. Hubble, I can't say we were the very first to try it, but I think we were the first to definitively use, in an extensive way, the transiting technique for detecting exoplanets, planets in orbits around other stars. And, certainly, we were the first to demonstrate the existence of an exoplanet atmosphere. HD 209458, I think, was the star that was mentioned by Mark Clampin.

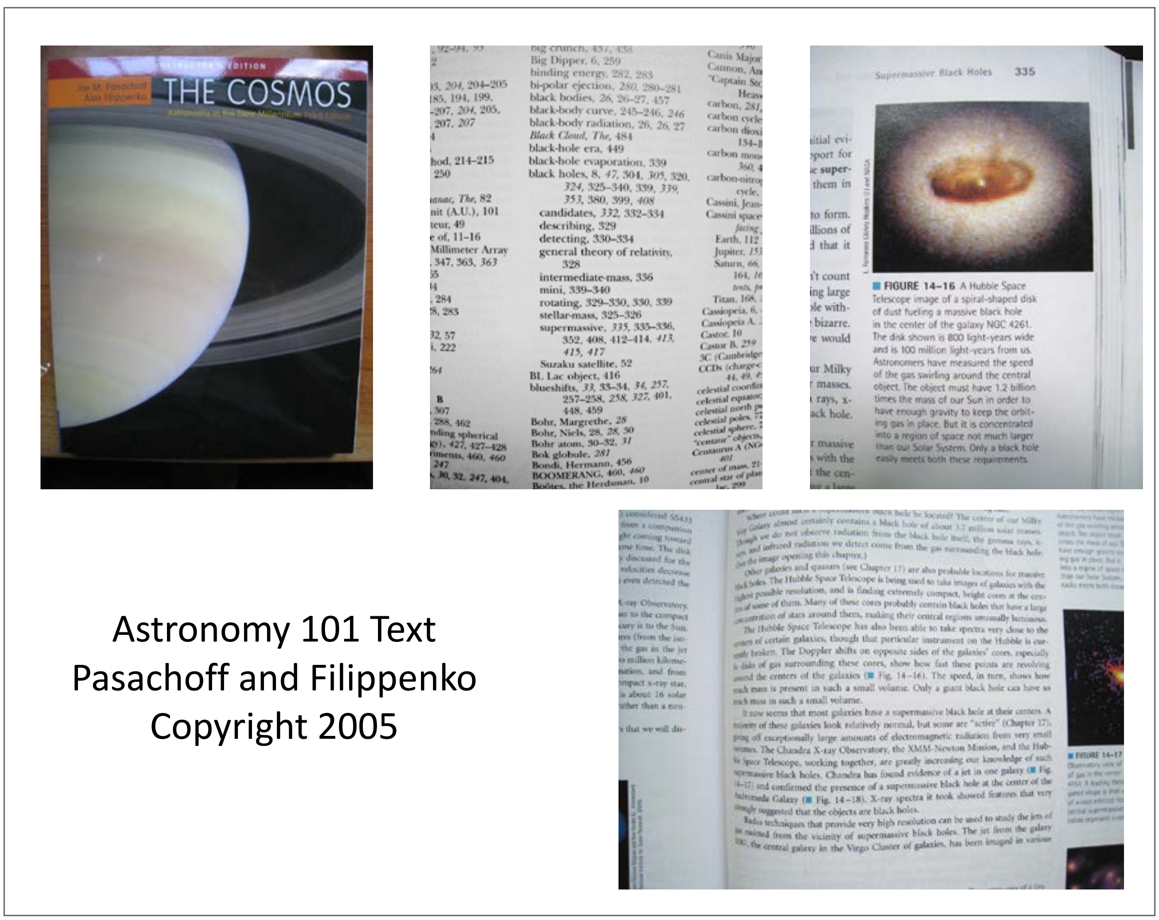
Villard: Sure.

Leckrone: The astronomers observed the sodium D-lines, so there was excess sodium in the atmosphere, and that was a very small beginning. And now combining Hubble and Webb, that is the UV, optical, and infrared wavelength bands together—and I think we'll have some discussion about that a little later here—you can actually go looking for the full chemical composition of exoplanet atmospheres, the haze, cloud structure, that sort of thing. Who could have imagined that? That we could actually not only detect, but study in some detail, atmospheres around planets that don't belong to our own solar system.

Nothing about near-Earth asteroids, although during 1994 July, the Shoemaker-Levy 9 event, where 22 fragments from Shoemaker-Levy 9 crashed into the upper atmosphere of Jupiter. Heidi Hammel was a big part of the Hubble activity during that wonderful week. Certainly, I had the most fun that week I ever had on Hubble. And so, the impact gave people pause on the Earth about what if this sort of thing happens to the Earth? And in particular, during that week or shortly thereafter, United States Congress took notice and said, hmm, what happens to us if fragments like this should hit Earth? And Jupiter, maybe the people who live on Jupiter didn't have to worry about it so much, but we would have to. So, they initiated programs with NASA and other entities to go hunting for all the near-Earth asteroids that could be cataloged, so we'd at least know what we're facing. Finally, in going through this list, I'm listing things that do not exist in my textbook, but that's an old list. In a sense, we've been living with these topics for quite some time now, and we're accustomed to they're being a normal part of astronomical research.

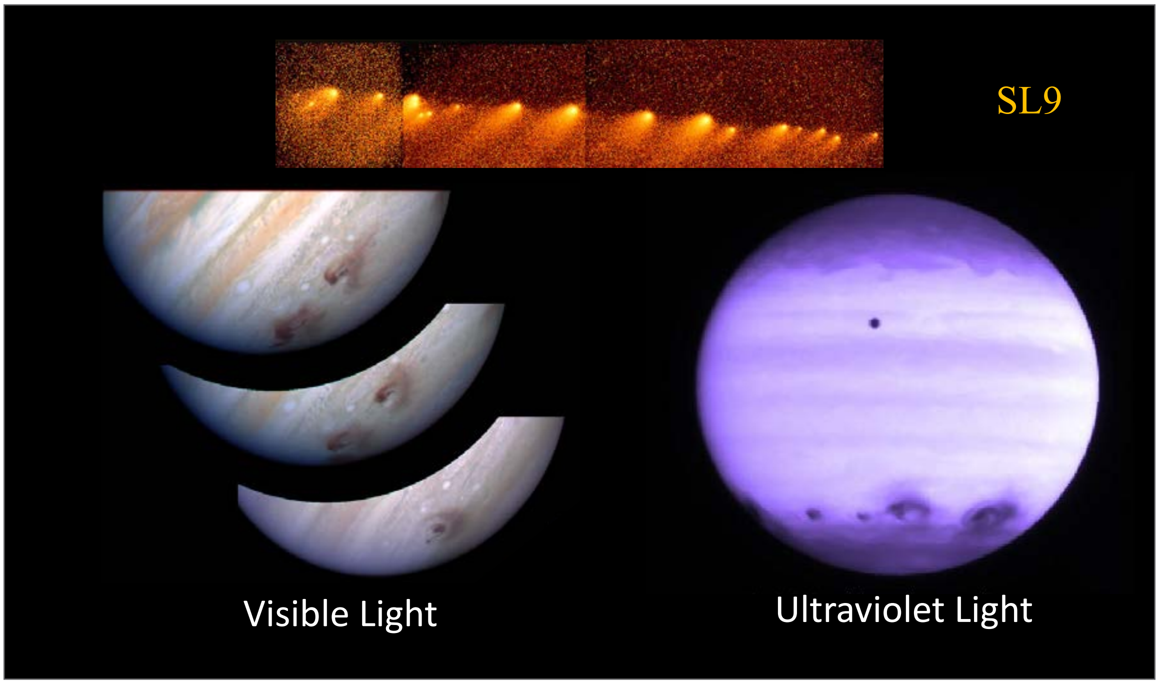
But there's one more thing I want to mention, and Adam Riess, if he could've been here, wasn't able to make it to the meeting, is the one who would really be able to discuss this in detail. But there's currently a wild debate going on, on what's called tension in the Hubble constant. And Adam has been working with his team for many, many years to precisely calibrate, more precisely calibrate Hubble. And that's another kind of advancement, an evolutionary advancement you can make in this observatory or an observatory like this that doesn't require a servicing mission or space shuttles. But it requires diligent work and very detailed and difficult work over many years to really calibrate and beat the calibration of the systems in the telescope, the instruments and the cameras, and so forth, beat them into submission, as it were, to really accurately calibrate the telescope.

And the consequence of that is that Hubble measures to 3 percent the current value of the Hubble constant, the value at which the universe is currently expanding. And they get a number 73 plus or minus 2.5, and I won't give you the units, it's too long. But other observatories that look back to the big bang era and the cosmic microwave background coming out of the big bang have their own ways of estimating what the Hubble constant should be, and they get a number 67 plus or minus a very small error bar. So, the point is that there's a tension between those two numbers, and their separation is wide enough that we can't figure it. We don't know why they don't agree. And there's the suggestion that maybe there's brand new physics here, and so you're talking about a topic that's maybe just a few years old now, and it's new. It's new research, and it advances because of the way Hubble people calibrate and use Hubble has advanced. That's all I've got to say.



Leckrone: Let's advance one. There you go. So, this is an Astronomy 101 text from Pasachoff and Filippenko, 15 years or sorry, four decades after my textbook, 15 years after the Hubble launch. And you can see, there's an extensive discussion of Hubble's observation of black holes in the nuclei of galaxies, so modern textbooks are, by all means, catching up. Okay, there we go.

Villard: Ken? There we go.

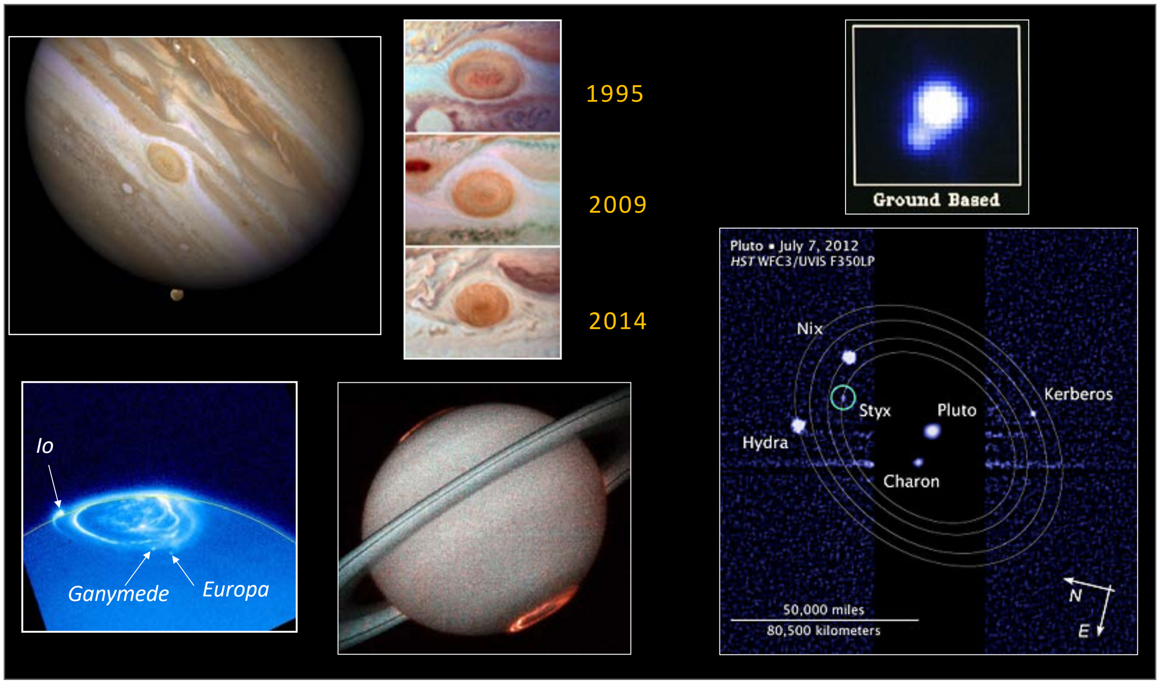


Carpenter: Okay, thank you, Ray. When I was asked to summarize solar system science in two slides, the first one was easy as you can tell by the fact that it's been mentioned several times already. Shoemaker-Levy 9 has to be among the top of the exciting results from Hubble on the solar system. The top image here shows a mosaic of images taken back in 1993, the year before the impacts, and shows some or maybe all of the 20-plus pieces that the comet broke into. It was determined when one looked at the orbital trajectory of these pieces that the next time around the Sun, they were actually going to hit Jupiter. So, immediately, the community jumped into action trying to get every telescope possible to look at this event. Although I believe there were issues convincing folks that Hubble should look at it because it wasn't clear that we'd see anything. There was a big concern that we might have this huge effort, turn the instruments on it, and see the normal Jupiter upper atmosphere.

Fortunately, when we did look at it, we saw not only features in visible light, which you see on the left-hand side here, features that are, I think, 5 diameters across, and the different sequence of imaging from the bottom to the top. I actually cut off the one that was blank before the impact, so you could see the other better. But if you go into ultraviolet light, you even see a more extensive set of impact zones spread out over perhaps even more distances. And on the right one, you see a shadow of one of the moons going across the image serendipitously as we're looking at it.

So, it turned out to be a huge event. People saw all sorts of different telescopes. Hubble, in addition to doing this imaging, actually did spectroscopy on it and saw a very rich emission line spectrum in the UV. And I was actually astonished when I looked at it and started to identify the lines. They're the same emission lines you see from the outer atmospheres of cool stars in their chromospheres, different intensities, slightly different temperature ranges. I was like, this could be

Aldebaran or one of their famous red-giant star. So, we had a little fun doing some comparisons there and trying to extract temperatures and the like.

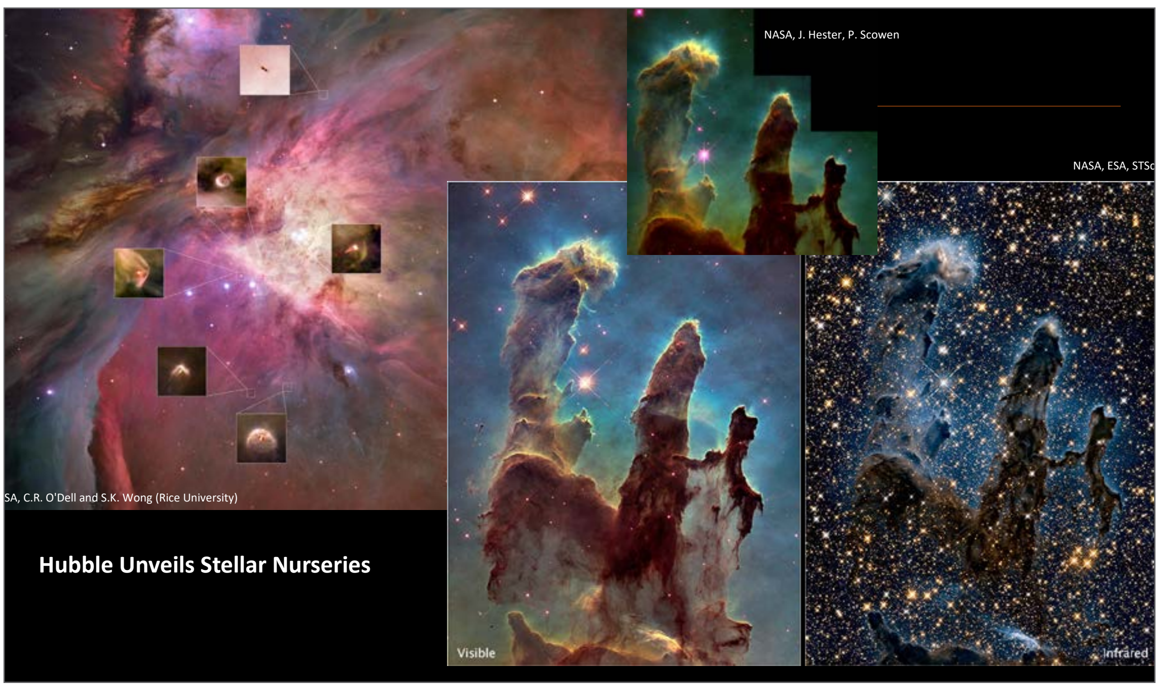


Next slide. Okay, and this is my attempt to gather some other highlights from the rest of solar system science. In the upper left, the image of Jupiter and one of the moons, and then expanded in that three-image panel is a close-up on the Great Red Spot. And as probably everybody knows, there is a pattern developing now where the diameter of the Great Red Spot has been decreasing relatively rapidly. I mean, this thing has been in the atmosphere for 300 years since the time of Galileo. And in our lifetimes and in the lifetime of Hubble, it's actually gone into this massive change where it's both shrinking, and I was just reading last night, the outer loop of the Red Spot is actually accelerating in velocity. So the winds are getting stronger as it shrinks, and the winds in the center, circulations there are actually slowing down. So, this ought to be a clue to the people who are modeling the atmosphere as to exactly how it's working, but so far, I haven't seen a detailed explanation of that.

In the upper right, you see the best ground based imaging of the Pluto system prior to Hubble. So, you see Pluto and the largest moon, Charon, just barely resolve from it. By the time Hubble finished observing the system or by the time you gathered the observations through July 7th of 2012—2017, it must be, before New Horizons, anyways, got to Jupiter, we had filled out the inventory of the Pluto system to include four additional moons. And we did it in time to send the information to the New Horizons team and say, a) don't hit these, guys, and b) could you maybe get a picture as you went by? And I think they did a pretty good job of that, and that is a really excellent example of different NASA spacecraft working together to get better science out in the end than either one would get on its own.

And then finally, on the lower left, two pictures of Jupiter and Saturn showing the bright aurora. On the Saturn picture, you see extremely bright aurora in the UV at both the south and a little bit at the north pole. And then on the Jupiter photo, we're zooming in on the northern hemisphere, and then you see the same ring-like structure that you see at Saturn, but you see these bright spots. And the three of them are labeled the moons of Jupiter that are known to have magnetic flux tubes connecting them to the surface. And this fact that those existed and were going to impact the surface there, funnel high energy particles down there, and cause these emissions was modeled and predicted before our observations. And the observations showed that they were bang on, just a wonderful case of predictive theoretical calculations being right on the spot. It reminded me a little bit about when they showed the 3-degree background radiation and showed the COBE results where the points just went straight in line. This is similar, and it's a wonderful convergence of theory and observation.

Villard: Okay, Jennifer?



Wiseman: Okay, thank you, Ken. So, what we're doing is each of us were tasked with selecting just one or two highlights of Hubble's scientific achievements, especially in the past. And then later in our conversation, we're going to share with you some highlights of what we're doing with Hubble now and in the future. But this has been very painful to try to select one or two things when there are so many wonderful things we could be talking about. My regime here for this discussion is star formation, and Hubble really unveiled a lot of what we would now call stellar nurseries, places where we now know stars are still actively in the process of forming.

So, you've seen some of these before, and I'll start out on the right here. The upper right is the classic image of the part of the Eagle Nebula or M16 that was famously called the Pillars of Creation. And, Ray, did you say you were the one who came up with that?

Villard: Me and Ginger French.

Wiseman: Okay, all right, so. But basically, it's a place where stars are still continuing to form. And then talking about the value of the servicing missions, when we put in the new Wide Field Camera 3, in the last servicing mission, we went back to the Eagle Nebula and looked at the Pillars again. And so, in the bottom there, you see the Hubble image on the left of the Pillars in visible light, and we're able to cover a larger field of view and see a little more detail with this image.

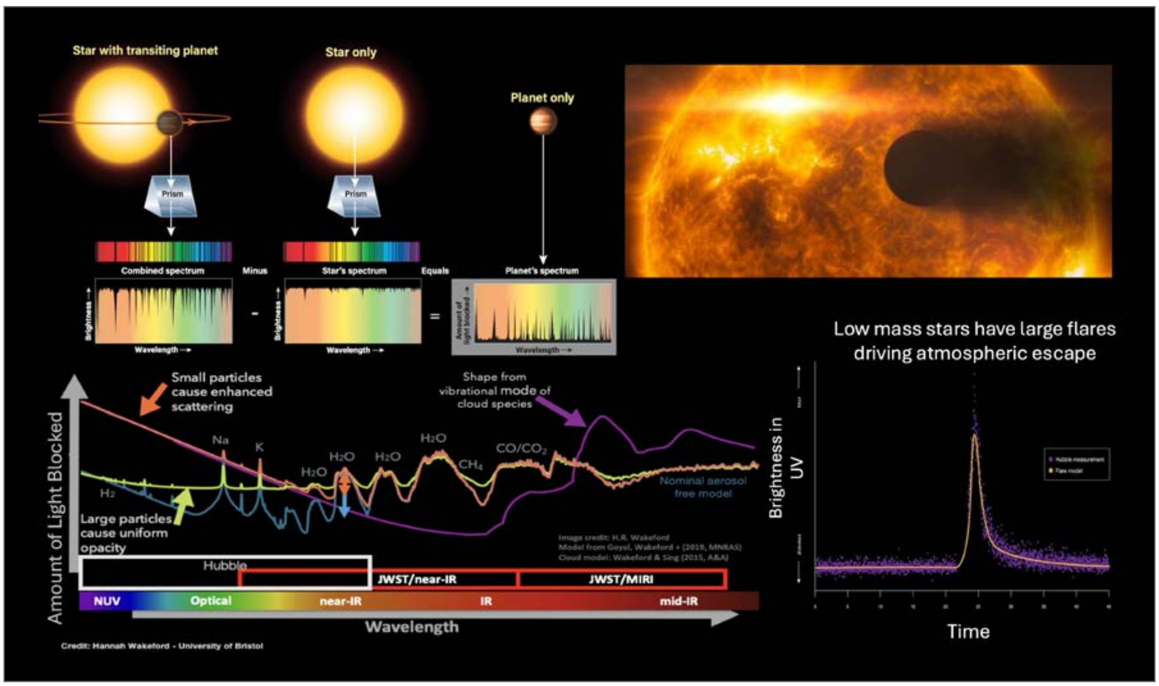
And also in visible light, you can really get more of the structure of the cloud, right? You can see the columns. We know that these columns of dust are common in regions where massive stars have recently formed. Because massive stars form relatively quickly, and the radiation from those stars can ionize surrounding gas, and winds from those stars can plow through the surrounding cloud and blow away the wispier material, leaving behind for a while, the more dense clumps, and those dense clumps can protect a wake behind them. So, pillars always point toward a cluster of massive stars that are recently formed. In these images, you can't see that cluster of massive stars, which are off the top of the images, but you can see these pillars being carved out from the wind. And, of course, these pillars are the denser leftover material, and it's in dense places where we expect stars to continue to form, the lower mass stars that take more time.

From that early image at the top, which I think was 1995, and the lower image taken, I think, in 2014, you could actually do a comparison and see that there are little jet-like structures. These are protostellar jets that are expelled. As young stars are forming, some of the accreting material gets caught up in magnetic fields around the protostar and get actually ejected out the magnetic poles of the young, forming star. Those baby stars are often too embedded to see, but you can see these jets. And between these two images over time, you could see these jets having actually moved in a measurable way.

The lower right is the same region with Hubble, but looking in the near infrared with the Wide Field Camera 3, which is a panchromatic camera allowing us to see ultraviolet, visible, and near-infrared light. And, whoa, you get a whole lot of different information looking in the near IR. You don't see all the structure that you see in the visible, but you can see through a lot of the dust, and see more stars in the whole region, and see into these pillars where young stars are coalescing. So, Hubble really has opened our eyes in different wavelengths of light to see what a stellar nursery looks like and how it changes over even the short amounts of time between earlier images and earlier instruments on Hubble and looking at it again with later instruments in other wavelength bands.

On the left, is the Orion Nebula, and that's one of the first things any new telescope ever looks at is the Orion Nebula. It's such a beautiful, bright, ionized region where massive stars have recently formed. They're ionizing the gas. But when we looked at it with Hubble, even before the repair, like in 1992, even before the initial repair, the Orion Nebula was showing signs of these little objects that had little cloaks around them. And Bob O'Dell and his scientific colleagues discovered these things in Hubble images, called them proplyds, or protoplanetary discs, shortened to proplyds, little cocoons around forming stars. And it seems that most of the stars that are still forming in the Orion region have discs of dusty material. Some of it's being photo-evaporated by this intense radiation from the massive stars that have already formed, but you can see the little cocoons around them. And now, we know that these discs that form around stars as they are in the process of forming are the zones where planets are in the process of forming. And so that has led to this study of planet-formation zones, and of course, as we know, eventually the discoveries of exoplanets and the follow-up studies of the nature of those exoplanets by Hubble, and Webb, and other telescopes.

So this, I think, is very profound because Hubble showed us that the universe is not stagnant. That stars are continuing to viciously form, and they vibrantly interact with their environments, which affects the next generations of star formation. Stars are forming, stars are dying, all of that is interacting with these larger nebular environments, and I think Hubble opened our eyes to how active our universe is. So with that, I will pass it on to Julia.



Roman-Duval: Yes.

Villard: Okay, from stars to those things around stars, exoplanets.

Roman-Duval: Even though my field is the interstellar medium, I decided to actually take on exoplanets and stars with Hubble. I sympathize, Jennifer, it's hard to pick a few things. So, Hubble was launched in 1990. It was designed in the '70s and '80s, and so when it was being developed, we did not know of any exoplanets out there. The first one wasn't discovered until '92, and the first exoplanet around a sun-like star wasn't discovered until '95. And yet since the 2000s, right, Hubble has been leading the way in exoplanet research, and now alongside Webb, which is a very powerful duo, the sum is definitely more powerful than the parts.

And especially using this transit method that David was mentioning, where you have the light from the host star that passes through the atmosphere of an exoplanet on its way to us, to Hubble. And by comparing the spectra of the system when the planet is in front of it versus when it's behind it, you can actually derive the spectrum of the exoplanet atmosphere and infer key properties like its composition and pressure or even the presence of clouds and hazes.

And so, you can see the spectrum as an example here on the bottom where the UV optical range of Hubble is really, really key to characterize those atmospheres. And in fact, there was a recent study a couple of years ago that showed that you cannot understand clouds and hazes with Webb alone. You really need the UV optical coverage of Hubble. And we can do this with Hubble thanks to the servicing mission, for which I'm immensely grateful to the astronauts, and all the engineers and scientists who worked on those and made those possible, but also with new capabilities that were allowed by instrument configuration and software. For example, the spatial scanning on Wide Field Camera 3, which really enabled this transit technique to be applied to a broad range of exoplanetary systems.

And so, thanks to that, Hubble actually had a lot of first discoveries in exoplanet research. Starting in 2001 with the first atmospheric composition characterization, the first detection of organic molecule methane in an atmosphere in 2008. It was the first detection of water on a super Earth in the habitable zone in the last decade or so, and it keeps coming, right? A couple of years ago, water was detected around the smallest ever exoplanet, that was in 2024. And with Webb up there, we expect that that's going to continue in an even more impactful way.

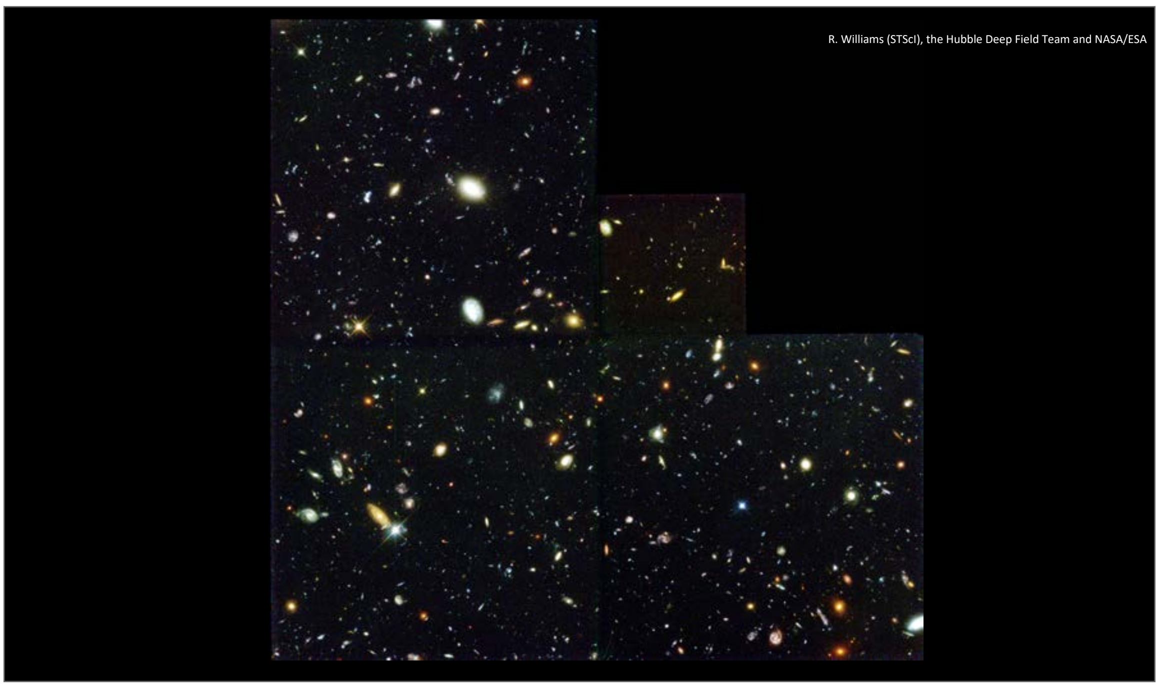
So, in addition to that, the most stars in the universe are small stars with masses even smaller than the Sun. Those stars tend to be very active in the ultraviolet and x-ray light, which is not very friendly with sustaining an atmosphere and habitability. And so, Hubble, with its UV optical capability, has been key to actually characterize the radiation environment around those low-mass stars that are hosting exoplanets and even catching atmospheres escaping in real time, thanks to, especially, for example, the Lyman-Alpha line in the ultraviolet. So, there's been a lot of papers recently really trying to get at which exoplanets could be habitable and which not, and which have atmospheric escape. And we can also monitor the frequency and magnitude of those giant flares on those low-mass stars that are hosting exoplanets. So, I'll get to that in a bit later, but I think that's really helpful in providing context to the Webb Telescope for understanding exoplanet formation, atmospheric escape, and habitability. So that's for exoplanets and low-mass stars.

I would also like to touch base on massive stars as the former lead of the ULLYSES program. ULLYSES was a large Director's Discretionary program, just like the Hubble Deep Field, the Trade Field, and the Frontier Fields. And so those were large investments of Hubble time that really changed the direction of the field and even allowed astronomers to ask questions they didn't know how to ask. And so, with ULLYSES, we dedicated a thousand orbits to study massive stars in the nearby universe, especially trying to characterize how their very powerful winds change as the metal content of the host galaxy changes. So at low metallicity, targeting, for example, our closest neighbor galaxies, the Large and Small Magellanic Clouds.

And most of the diagnostics for those stars are in the ultraviolet. So using ultraviolet spectroscopy, you are able to see how clumpy those winds are and how fast they are. And that also puts some constraints on how they can disrupt the surrounding interstellar medium and drive the evolution of galaxies, in particular by injecting newly minted elements that will later be incorporating into new generations of stars, exoplanets, and life itself.

Hubble is being very heavily used to try to understand those stars, their winds, their composition, and their impact on their host galaxies in the nearby universe but now pushing the frontier to even the edge of the local group. So studying very metal-deficient galaxies like Sextans A, for example, and really opening new frontiers in understanding those very massive stars. And those are key to galaxy evolution, which I think is a nice segue to what Amber is about to say.

Villard: Okay, Amber, and nice segue, thank you for setting that up, too.



Straughn: Great, well, this whole gathering is called Beyond the Deep Field, but I don't think we can let these two days pass without actually talking about the original Hubble Deep Field. This image came out when I was in the 10th grade. I knew from the time I was a little kid I wanted to be a scientist, and I was already leaning towards astronomy, but it really was this image that made me know that I wanted to be an astronomer. And we talked about how Hubble has changed astronomy and how it's changed our textbooks, but I think it's also so important, and we've already talked about this some today, to really recognize and honor how Hubble has changed us as a society, as humanity, and all of us personally as individuals. It changed my trajectory, and I think all of us here on stage could say that, and probably all of us here today could say that it's changed us as individuals.

And this image, as you all know I'm sure, didn't have to be. It was a huge risk. It was taking this telescope, whose time was so precious, and saying, let's point at a blank piece of sky and just see what happens, and that was wild, that was innovative. It didn't have to happen, but the people that designed this were bold enough to do that, and that's remarkable. And this single image really did give birth to the whole field of galaxy evolution. What I studied today in my research started with this image. This was the first time that we saw this incredible structure in the early universe. We saw that these very distant galaxies looked completely different than the galaxies nearby. They're irregular, and they're clumpy, and, oh, there are some distant spiral galaxies, but there are some of these galaxies with shapes that we'd never seen before, and they are chains and clumps, and what's going on? It was just like this whole new field that opened up with this single image.

And I remember as a kid just reading the articles in *Astronomy* magazine and this was before, well, the Internet. We talked about how the Internet was coincident with Hubble, but I didn't have Internet in rural Arkansas when I was in the 10th grade, and so I was reading this in *Astronomy* magazine and in the newspapers. And I think just the fact that that we were able to see the universe really in a brand-new way is incredible.

And of course, following on to this, we've had multiple iterations of Deep Fields. We kept pointing at this part of the sky, we pointed Hubble at the south, we got the southern Deep Field, we have the good surveys, and on and on and on into, of course, the Deep Fields that we have with Webb. And so, I think this image is just such a perfect illustration of how Hubble did what it was designed to do, but it also paved the way to the future of learning things now with our telescopes today that we never expected.

And, of course, this gets into cosmology, which we've already talked about, this incredible discovery of dark energy. The surprising discovery that the universe is accelerating in its expansion, an observation and a discovery that could not have happened without Hubble. Hubble has, of course, helped us refine the age of the universe, the expansion rate. All of these critical things about how the universe works were really made possible by Hubble, and this image is definitely what got that whole field really kicked off in earnest.

Villard: That's wonderful, and we're going to change gears now. I did want to say something about the HDFO, and Dave can help me out. It was debated, right, whether to do it?

Leckrone: Yeah.

Villard: And if it came up blank, the public would laugh. No, the public wouldn't laugh. Anything you find out new about the universe is telling you something.

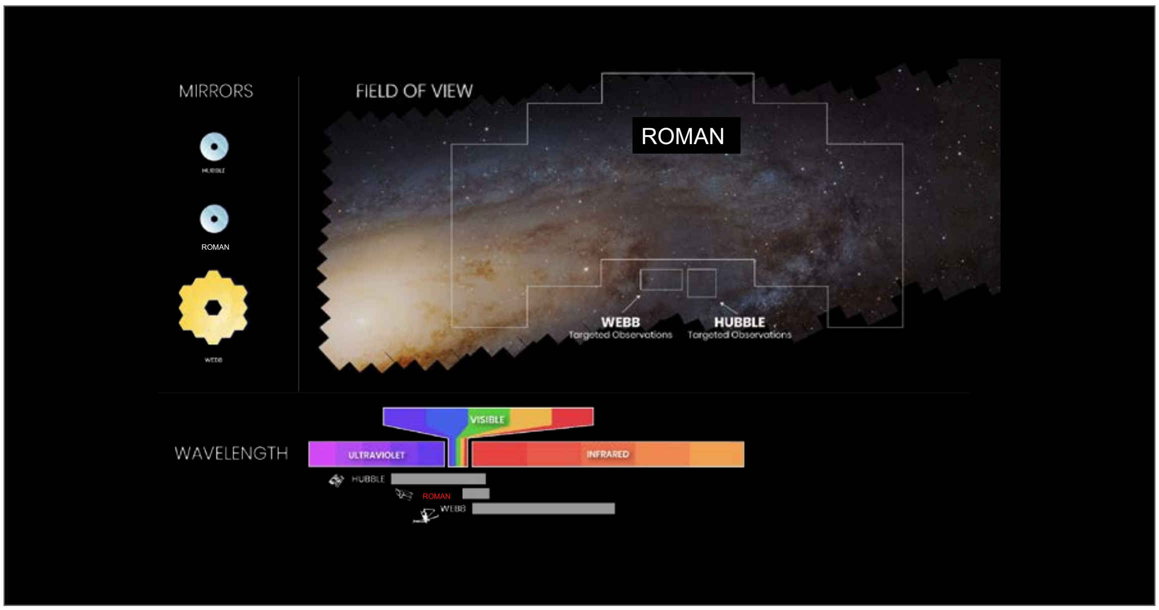
Leckrone: Yeah, no, you're right, it was very controversial. There was a paper that suggested that if all the galaxies in the universe are similar to those nearby us, as you look farther and farther back, those distant galaxies will disappear into the background, and you won't see anything. And so, do you want to devote that kind of telescope time and possibly not see anything at all? So, you can thank Bob Williams for the courage to press on with that.

Villard: And Williams, to me, and I'm moving with this, but the core of science is looking or going into the unknown, right? That's the very core, to find something that nobody has seen before, and the HDF in Hubble is the epitome of that.

Leckrone: Yeah.

Villard: So, we're going to open it up to a discussion, a dialogue among the panel members. I do want to kick it off with the members, and we have additional slides. What's Hubble doing now, and what's Hubble going to do in the future? Hubble has an important future ahead, especially with the synergy with the other observatories up there. But let me kick that off with Dave, and I think we've got a picture for you, don't we?

Leckrone: Yes, there it is.



Villard: Because we have Roman launching in a few months, the wide field version of Hubble.

Leckrone: Well, a couple of major things to see in this slide. First of all, Hubble does detailed observations in relatively small fields of view in the sky. Webb is similar in its relatively small fields of view in the sky. The actual field observed in a given observation depends on the particular instrument on board the observatory. But those two are a smaller field dedicated to individual targets.

Roman, as you can see, has about a hundred times the field of view—and I think that's the correct number—about a hundred times the field of view with its cluster of detectors. So, it's more of a survey telescope, which is capable, by the way, of going as deep as Hubble. But the one major difference among Roman, Webb, and Hubble, is Hubble is primarily ultraviolet, optical, and very near infrared. The other two telescopes, Webb and Roman, are primarily infrared telescopes. The idea being that if you want to observe far back in time and far out across the universe, the light from the most distant objects in the universe is redshifted by the expansion of the fabric of space itself. So, if you want to observe near the Big Bang or slightly after the Big Bang, you have to go to the deep infrared, but what about ultraviolet and optical? Hubble really covers that waterfront very well, and still does, and we hope for a long time into the future.

So, Webb is primarily infrared, Roman is primarily infrared, very little overlap with the optical. Webb has some slight overlap, but not a lot, and then you have to rely on Hubble for the UV and optical. The thing that we just saw from Julia just shows very nicely how you take the UV and optical spectrum of an exoplanet atmosphere and attach that to or, yeah, ground it to the spectrum taken with Webb and its spectrographs. And you get the full panoply of possibilities in terms of molecules you could detect and maybe even search for signs of life sometime in the future. I know there's another observatory coming along to emphasize that, but I always have my hopes before I leave this planet that somebody will say they've detected actual life.

Villard: Okay, Ken, you don't have a slide, but do you want to pick up Hubble's future?

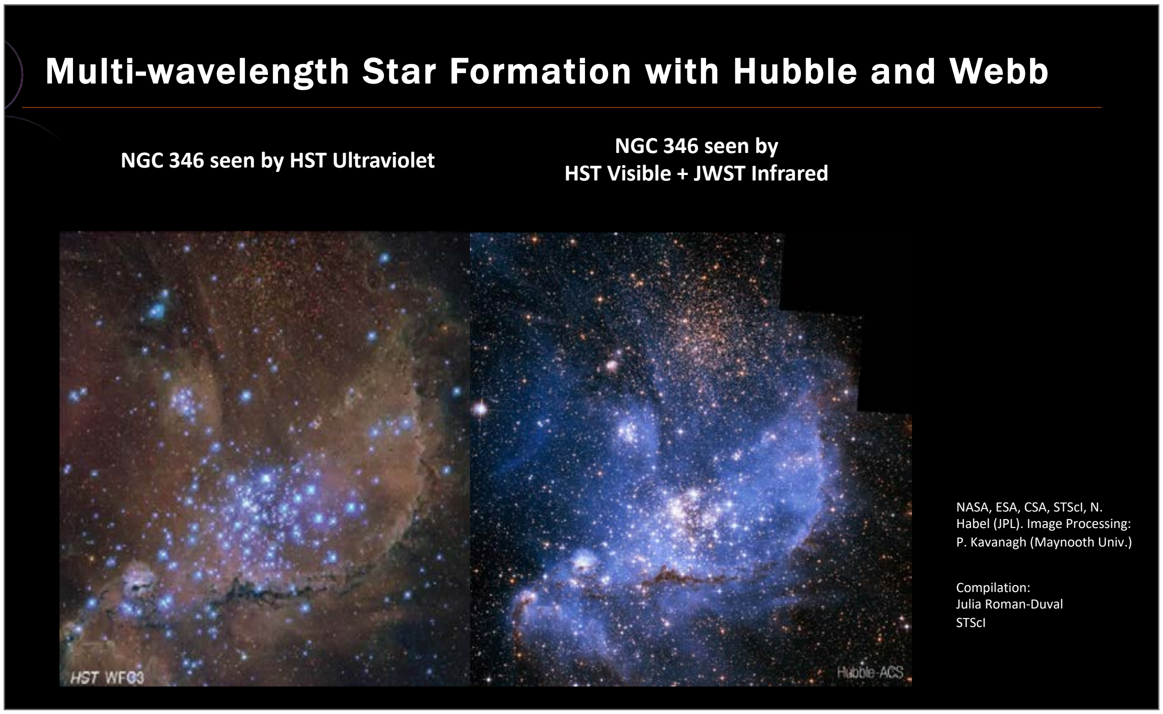
Carpenter: I don't have a slide here, but one additional program that I want to mention that extends into the future, so following along that, is something called the Outer Planet Atmospheres Legacy program or OPAL. And that is intended to monitor the outer atmospheres of the gas giant planets regularly for as long as Hubble keeps going. That gives us a chance to do long-term studies of the variations in the winds, and the weather, the climate, and we might be going long enough, we can start talking about climate changes as part of this. But that's already been running for quite a number of years.

You may think, well, why do we really need to keep doing this? You've got to remember that, especially the more distant outer planets, Uranus has a year that's 84 Earth years long. So, we haven't even come close to covering a significant fraction of one year's orbit to look at the seasonal changes for instance, and even on the closer ones like Jupiter at 12 years think it is. It would be nice to have more than one orbit, so you can see what is a regular, repeating pattern in terms of seasonal changes and what is unique as you go along. So, I just want to point out that that exists, it's going forward, and there'll be other things we'll be looking for in the future. Now, maybe prepare for the next interstellar interloper that comes by, and maybe next time it will be from Rama.

Villard: Probably we'll be happy. Jennifer?

Wiseman: Okay, so the question is, what are we doing with Hubble going into the future? I want to get back to my theme of star formation. So, we're in star and planet zone, star formation, and I think that one of the powerful scientific advantages that we have now—it's already been mentioned by Dave—is having multiple, complementary astronomical platforms. So that we can study whatever astronomical entity we want to study now with multiple, powerful wavelength bands. So that gives us more information than we would ever have with any of these facilities on their own, whether we're looking at planets, or stars, or galaxies.

So here, you can see one of these nebulae where stars are actively forming. This is NGC 346, which is in the Small Magellanic Cloud. So, this is one of the little, dwarf sister galaxies near our Milky Way, but it's much more primitive than the Milky Way. It hasn't had all the mineral enrichment of heavier elements from many generations of stars as vigorously as the Milky Way has. So, we're interested in how stars and their planetary systems would form in a more primitive environment with an eye to thinking about how they may have formed in the early universe. We learned so much more now when we've got Hubble's visible light, Hubble's ultraviolet light, and Webb's light that we can use all together.



So, on the left here, you see this region in NGC 346 in HST, and particularly in the ultraviolet. That's that high-energy radiation that you particularly see from hot blue stars that have recently formed. So, you see that cluster of blue stars and the glow of the nebula, the ionized region around those stars. On the right, you see that same region in visible light, so you can see a lot more of this ionized gas, the nebular material around and between the stars. You can get a sense of how the stars and the protostars that are still forming are interacting with the environment. And then it's going back and forth between that and infrared light from the Webb Telescope. Here, you can see the dusty filaments that are being heated up and lit up by this whole region. You can see where the bulk of the material actually is. By having all of this information together, the dust, the gas, the nebula, the stars, and seeing how they interact, you can get a much better sense of the dynamics of how a star-forming region actually functions and the content of the region as well. So, I think this is just an example of how Hubble is being used very powerfully right now for science that often involves science from other observatories, and we work in complement. I have a lot more examples of that, but maybe we can get to it in our later discussion.

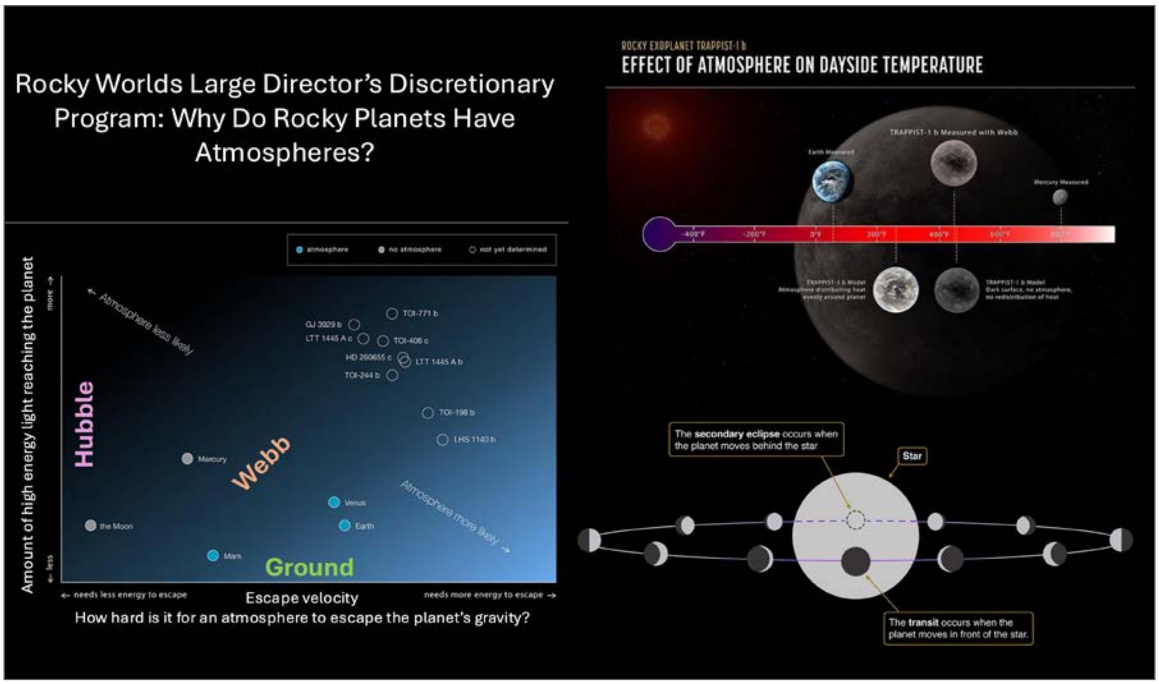
I did want to mention that, talking about these protostellar jets, there's a beautiful one on the front of your program. So, I should have mentioned that before, but what a great selection for this symposium. This is what we call a Herbig-Haro jet, but it's basically, you can't see the baby star, but you can see the jet being ejected out from the magnetic poles of the star, and it's quite beautiful. So, that's it for me for the moment.

Villard: Of course, in PR, we had to call it a lightsaber.

Wiseman: Yes.

Villard: That got a lot of press by the way. Frontier fields, we said galaxies, there was some movie, *Guardians of the Galaxy*, that got coverage. Anyway. Julia, planets, to boldly go—

Roman-Duval: Yeah, so—yeah, thanks, Ray.



Roman-Duval: We have a lot to look forward to with Hubble and exoplanet and stellar research. And I will say, right, that everything on Hubble is working wonderfully, and so I think we can actually look forward to many years of continued transformative science.

One thing I'm particularly excited about in the field of exoplanets is the Rocky Worlds program. So, in the same lineage as the Deep Field, Ultra-Deep Field, Frontier Fields, ULLYSES, Rocky Worlds is the new large Director's Discretionary program that is being run from Space Telescope. And it is actually joint with Webb in pursuing a study of what is called the cosmic shoreline. And the cosmic shoreline is this demarcation between rocky worlds that are more or less likely to have an atmosphere around them. And so, what Rocky Worlds is doing is it's using Hubble, 250 orbits of Hubble, to study the radiation environment around low-mass stars, so with masses lower than that of the Sun, maybe a half, two-thirds of the Sun mass. And, in particular, monitoring those energetic flares that I was mentioning before to provide context in the kind of environment where those rocky worlds are forming and evolving. From the ground, we are getting the gravity of the exoplanet, and that impacts its ability to retain its atmosphere, and then Webb is measuring eclipses for this exoplanet. So that's when the planet actually passes behind the star, and in that case, you actually lose the light of those planets in your images or spectra.

It turns out that when you have a planet like Earth with an atmosphere, you have winds, and the winds can redistribute energy and temperature around the planet pretty efficiently, and so the temperature is relatively uniform between the night and the day. When you have a rocky world that is bare rock, it's very hot in the day and it's very cold at night, and you can actually capture that during the eclipse. If you have a very deep eclipse, so you lose a lot of light when the planet goes behind the star, that means that you actually have no atmosphere. If your eclipse is shallower, you probably have a planet like Earth with an atmosphere that can redistribute energy and temperature.

And so, the Rocky Worlds program is exploring this effect to try to determine which of the nine target rocky worlds do host exoplanet atmospheres. And that's really going to be a first step I think in pursuing larger samples with Hab Worlds. This lays out the groundwork for determining the properties of the exoplanetary system that are conducive to the presence of an atmosphere or not. So, we'll be doing that for the next two or three years, and I'm sure the results of these observations will continue to be published for years and years to come just like that's been the case for the previous large DD programs like the Frontier Fields and ULLYSES for example.

There are other community-led programs, even large ones, that are also doing some really interesting work with exoplanet atmospheres. In particular, I want to mention the Multi-Cycle Treasury program called STELa, which is using COS and STIS, so UV spectroscopy, to measure atmospheric escape around exoplanets orbiting low-mass stars. And so, you'll probably hear more in the news about this in the coming years. This program is still ongoing.

And then more generally, right, exploring the synergy between Webb and Hubble, studying the full range of the spectrum of exoplanet transits so that we can understand the composition of atmospheres, the properties of the clouds and hazes. The diagnostics of which are primarily in the ultraviolet and optical. So, lots to look forward to, and I hope we can have another one of those maybe in five years to regroup, so.

Villard: Now, Amber, we're going to deal with galaxies again and the synergy again between the infrared and the visible, and that's like peanut butter and jelly, right? You can't have one without the other?

Straughn: Right, and the galaxies I study are actually a lot more distant than this one, but I think this particular example just is a perfect visual demonstrator of what Dave was saying about why it's so important that we have these multiple wavelengths to study these cosmic objects. So, obviously on the upper left here, we have infrared; lower right, we have the optical from Hubble. And essentially, what it boils down to is you just learn different things from studying the different types of light. So, in both nearby galaxies and also extending out to those more distant galaxies, the optical and the UV gives you more insight into current, ongoing hot star formation. Whereas in the infrared, you're getting a different view of the galaxy. You're getting the reprocessed dust and all of the different physical aspects of what are going on in the galaxies. And, again, this applies both nearby and as you extend further out in the universe.

It's so easy to see in an example like this of just visually why it's so important to have this multiwavelength data. And, of course, Hubble still is doing this important work for galaxy evolution studies by utilizing the UV and the optical data that we have. And we talked a lot today about how important archival data is, and that continues to be a really core part of galaxy evolution studies, combining Hubble data, ultraviolet, UV, and optical with the infrared data that we have from Webb.

And extending into the future, of course, this is going to be also critical, critical work as we look at Roman as becoming this wide-field view of detecting these rare cosmic objects that then we'll be able to follow up with both Webb, and Hubble to get that multiwavelength view. And really, just at the end of the day, a more complete picture, a more complete version of how the universe works.

Villard: Wonderful, I hope this gave you a holistic view of the incredible need for Hubble and its accomplishments. I want to switch gears now, take a step back to the broader societal and cultural context. So, I'm going to throw you guys a ringer before I get into our other questions. This quote is from a writer, he's widely published, you've probably never heard of him, but he's at Temple University. He says, "All 21st-century philosophy exists in the wake of the Hubble Telescope by allowing us to find cosmic meaning for the human species." What do you think? I didn't make that up. Anyway, I think it's cool. Okay, you all have anecdotes in terms of how Hubble has affected the public and communications you've had with the public.

Leckrone: I've got something else for you.

Villard: All right, give me something else.

Leckrone: My grandson just graduated with undergraduate degrees in physics and astronomy with a minor in mathematics. I didn't twist his arm, I didn't push him to do this, he just was interested, and so he's been successful so far. Katie Thornton was an astronaut on the first servicing mission, and she helped to install COSTAR. You may remember she threw the solar panel that wouldn't fully roll up, she threw it overboard, and classic Wagnerian pictures of that, it's just amazing. As I understand it, her daughter—I'm not sure what her daughter's age is, but surely late 20s by now or more. Her daughter did her thesis research with Hubble data. So, her daughter was, I guess, a little girl when Katie flew, and she grew up to go to graduate school and get her PhD in astronomy based on Hubble observations. And I thought the continuity, yeah, the heritage that Hubble people are passing along, both the scientific heritage, the literature and so forth. But just the fact that our children, and grandchildren, and maybe great-grandchildren will have been strongly affected by the Hubble Space Telescope. Now, I like that philosophy as well; I'd like to believe that's true. But closer to home, our kids are carrying the torch into the future, and I hope we can continue to give them the tools to expand their knowledge beyond this.

Villard: Yes, and the inspiration was interesting. You were in high school when the HDF came out? Somebody else, an astronomer told me, the spacewalks wanted them to be an astronomer, the Hubble servicing. Ken, do you have any anecdotes?

Carpenter: I don't have an anecdote, but I'll take the opportunity to just observe or make note of some of the observations that I've made of how Hubble has permeated our culture, and I'm sure other folks will have ideas here too. I was going to start with the historical list.

Last night, I was looking at Facebook, and one of the people I follow is a violin player, not Lindsey Stirling, a more junior person. But I zoomed in to listen to the latest creation, and this absolutely beautiful dress she had on, printed with, I believe, a Hubble image of a huge nebula. I couldn't quite figure out which one it was, but an absolutely gorgeous reproduction, I don't know what process they used, but you see that a lot, actually. It's got into the fashion world, I think, a fair amount. But you see Hubble images and data of various sorts on the side of Maryland U-Haul trucks. For instance, there's a picture, actually, of Hubble in that case. It's on record covers, and if you ask nicely, Amber may say something about one of her favorite record covers. So many books written about it. The list is just endless, and it's pretty wild the places where people have—I've got to show off the Hubble, and this is what I've got, so it's going to go on there.

Villard: An earlier speaker today said the beautiful Hubble pictures—and there's never enough of them—people can identify, right, with, and I think that is a huge thing. And the democratization, which people talked about, you can grab them on the Internet.

Carpenter: And there's a good illustration, as somebody mentioned this morning, the way *Star Trek* has worked with NASA for years. Mike Okuda, I think, is one of our great friends out there who grabs NASA images, lots of times Hubble, and inserts them into shows, I know Voyager's got a bunch. And *Strange New Worlds* actually has an episode in the 23rd century, which references Hubble, just the name Hubble, indicating it's still going to be around.

Wiseman: Be careful, Ken is a Trekkie, let's not let him get more on. I have a thought, too. I give quite a few public talks to different kinds of audiences, and I think what Hubble has done is reinvigorate some ancient philosophical questions—are we alone in the universe, how big is the universe, how long have we been here, how do we relate to the universe? Those are not new questions. But the accessibility that people have had since Hubble was launched to actually see visually the beauty of the universe, the activity that I showed about stars are still forming, stars are dying, and then seeing how the universe has changed over cosmic time by looking. We can actually use astronomy as a time machine, right, to look at things the way they were in deep history of the universe and see how they compare to how things are now. And we see that the universe has become more hospitable for life on at least one planet, so.

We now re-fertilize those ancient questions of could there be life elsewhere, how do we interact with the rest of the universe? And that fertilizes things beyond just the boundaries of formal science. I hear people who are inspired to write music based on Hubble images or to write poetry. I go to a lot of religious audiences who are very inspired by what we've seen with Hubble and other telescopes to enrich their own faith perspective. And so, what we've seen and discovered with Hubble and subsequent observatories is enriching many different aspects of the human experience.

Villard: Yeah, that's eloquently expressed. Julia?

Roman-Duval: I was 7 when Hubble launched, and I had decided when I was 11 in 1993, that I wanted to be an astrophysicist, so maybe Hubble had a little something to do with it. But my point is, I joined Hubble professionally pretty late in the game, so I may not have as many anecdotes as you do. But what I have seen is what you're saying, an overtake on culture. So, I don't know how many of you have seen the Bubble Nebula make the cover of *Vogue* last July, was it? Anyway, if you haven't, please look at it, it's amazing. And from that to the screensavers on the Transatlantic flight I took recently were a couple of images, and it's all over the airports, and the socks, and the shirts, the songs, the art on museums.

I think if you go out in the street and you ask someone if they know about Hubble, most people will say yes because it's part now of our culture and society. So that was a big shift, I think, in the model of those big flagships that completely democratized access to science to the public and the scientific community. And so, as a result of that, perhaps a lot of us take it for granted, and maybe we need to continue advocating to make sure that the newer generations are as privileged as we have been in getting access to those discoveries. I think it was Nancy Grace Roman who said, for the price of a night at the movies per year, every taxpayer can have access to 15 years of discovery. And so, of course, now, it's going to be more like maybe 40 years or plus, but—yeah, so, yeah.

Villard: Okay, Amber?

Straughn: Yeah, well, and the album cover, the band was Pearl Jam, just to get that in the record. Their album that came out in 2000 was a Hubble image on the cover, which made me very happy. I grew up in the '90s, so I've been a fan since then. But, yeah, it's incredible how the images have permeated our culture, and they're still so relevant today like today.

I was talking with some of the folks up here two weeks ago today. I was in Kenya at a leadership summit, and this group asked me to give a talk about NASA astronomy, so of course, I included Hubble images, I included Webb images. But I was with this group, I was the only scientist there, I was with this group of CEOs, and venture capitalists, and very wealthy people that put a lot of their money into conservation and philanthropy. And it was an awesome, incredible group of people, but it was not scientists, and I'm like, why do these people want to hear about space? But I tell you, it's resonant today with everyone.

These images bring something out in us, and this was talked about earlier on the history panel. There's something deeply human about discovery and about seeing these images that maybe on a deeper level remind us where we come from. This is all of us, we're not separate, this is part of us, we're part of the cosmos. It was really striking to me.

The day after I gave my talk to this group of venture capitalists, one of them came up to me the next day, and he was like, "We were talking at breakfast this morning about space and we were all just crying," and I'm like—you know. These telescopes have given this gift to us as humanity, and I think it goes so much beyond scientific learning, which obviously that's the point, that's important, that's the goal, but it's so much bigger than that. These telescopes are for all of us, and ultimately, they're made possible by all of us.

Villard: Hubble, for 35 years, the biggest NASA nonhuman project that keeps giving. Thirty-five years of popular support, that beats aging movie stars at this point. Hubble also is the only science instrument I can think of or science enterprise that people know on a first name basis, right? I can't think of anything else. Apollo, what? No, that's a sequel. Anyway, no, really, there was a movie, aliens were coming, there's a bunch of alien movies, but they said the Hubble looked at it. They didn't say the Hubble Space Telescope, they didn't say NASA's Hubble, they said, "Look at these pictures from Hubble," and I said, "Wow, that's a big deal for Hollywood," because even there, it's on a first-name basis. How has Hubble—and this was talked about earlier, but I'm going to get you guys' take on this—changed the way astronomers do astronomy? Anybody, jump in.

Leckrone: Well, somebody described this earlier. Astronomy used to be Edwin Hubble sitting all alone with the 100-inch telescope looking through an eyepiece. Now, you sit in a comfortable room down in Pasadena and use a computer to input your request for observations, and the data comes back down to you on your computer. And that's the Hubble; that's the space observing paradigm.

Villard: Right.

Leckrone: We don't send telescopes up in orbit, although the original concepts for Hubble included crude vehicles with photographic plates that they would develop in orbit.

Villard: We're running on, let me open the floor to questions.

Wiseman: Well can I—? While people are lining up, I would say that one of the exciting science realms of Hubble now is that we have this archive of data that spans decades plus new observations that we're continuing to do. So, a lot of our successful science observations use new observations and combine them with archival data to learn something that we could never learn with just a one-time snapshot observation. So, we can see, for example, as Ken mentioned, how the weather on planets is changing in our solar system over decades. We wouldn't know that if we didn't have this long archive. We can actually look where we see stellar explosions and look in the data to what was the precursor objects before the stellar explosion, so we can understand something about these supernovae and other types of stellar activity.

So, this kind of astronomy that dips into using a long archive as well as new observations is really phenomenal. We just published a few months ago, detection of an intermediate-mass black hole. You can't see an intermediate-mass black hole, but by having decades of data looking at a cluster of stars and watching their motion with the high-precision calibrations of Hubble, we were able to detect that there is a supermassive black hole in the core of Omega Centauri. So that's just something that comes to mind.

Roman-Duval: Yeah, I'll complement that by having science-ready data in the archive that any grad student or inexperienced researcher using Hubble for the first time can download and even use the archival tools to actually streamline the analysis of science data and get it into a paper in a pretty short timescale. And that used to be not the case, and I think it's a new model that the new NASA flagships are using, like Webb, and Roman, and Hubble in the future, to really maximize the science output of this large taxpayer investment.

Carpenter: In fact, I think you can see this taken almost to the extreme with the Roman Space Telescope, which is, in effect, for most of its observations, is going to be an archival-producing observatory. Because the data rate is so incredibly immense, something like 11 terabytes a day. This stuff is going to go into the archive, and people will pull it out of the archive and analyze it. And most of the grant proposals, for instance, will be more like archival proposals than new observing proposals because there are these huge surveys that are being taken that are defined in advance, producing this incredible amount of data. And a large number of the funded research is going to be to go into those predefined programs, take the data out, and analyze them. There will be opportunities for the community to generate new data saying, you're missing something over here that's important, and in that sense, it's more like a general observer program. But almost all the programs are going to be general investigator or archival research because of the very nature of the very large datasets that Roman's getting.

Leckrone: I was just going to ask Ken. With that amount of data available in the Roman archive, are we going to need AI to help us do the research?

Carpenter: Sure, there are people that will attempt to do that. We, as Julia mentioned, have our developing tools that observers can use to analyze these large volumes. Everything's going to be in the cloud, there'll be tools resident there, some people will write their own tools. But AI, to my knowledge, has not been brought into that yet. It's probably only a matter of time. I mean, there's all these concerns about fake results, etc., that you have to be very careful about. But you could use it, I could say, search for certain phenomena in these large datasets, and you're probably safe there, but be careful, yeah, don't quite have it right in your paper yet.

Roman-Duval: Yeah, I will say that there's already AI tools that are being used to study astrophysical anomalies in Hubble surveys. So, the community is thinking about it and maybe building some prototypes that maybe can be used for Roman.

Leckrone: I just remember the days when George Abell at Caltech, the Palomar 200-inch Sky Survey plates and looked at them individually through a magnifier. And with this incomprehensible amount of data that's going to come out of the Roman, I think you'd need some help.

Wiseman: Let me just follow on quickly because, as Julia mentioned, one team just recently did a little experiment with the Hubble Archive. And they wrote a little AI routine, which in less than two days, found hundreds of previously uncatalogued, anomalous galaxies that were misshapen because they're merging, and just like that. And so now, we can do all the follow-up studies, but that just is a sample of the power, I think, of these AI tools.

Villard: That's great. We're over the hour, does anybody have—? No questions, they're just flabbergasted.

Leckrone: It's been a long day.

Wiseman: I think that we could close by just reminding people that our esteemed historian, Robert Smith, here is wearing a Hubble image of Eagle Nebula—the Pillars of Creation—on his socks. Is that correct?

Smith: When I teach my undergraduates, I show them a slide with all the products they can get, showing the Pillars of Creation. They're always so disappointed when I show my socks.

Villard: Well, thank you all. It's been a long day, and I hope this was expanding your minds like the expanding universe, but there was only one Beatles, there's only one Hubble. I'm giving my age away, of course, but—

Wiseman: And thank you, thank you, Ray.

DAY TWO – June 5, 2026

Session Four

Partnerships Across Hubble's History

Moderator

Jim Jeletic, NASA

Panelists

Jennifer Lotz, STSci
Olivia Lupie, NASA
Chris Evans, ESA
Matt Mountain, AURA

Jeletic: All right, well, we're really here to talk about the partnerships, the history, the success, any challenges with them, and things like that, and partnerships are made for many reasons. Sometimes, they're made for budgetary reasons to help cover the cost for a particular mission; sometimes, they're made to get expertise; sometimes, they're just made for goodwill. So, Hubble has an awful lot of partnerships, and we know basically, and think about it, for the most part, as two major ones. And that's the one with the European Space Agency, ESA, and then one with the Space Telescope Science Institute, STScI. So, we're going to talk about those, but then we're definitely going to talk about these other partnerships, which I think are just as important, too, to the success of the mission.

So, we have a very nice senior panel here, so I'd like to first start and introduce Dr. Jennifer Lotz. She's the director of the Space Telescope Science Institute, an 850-person multi-mission operations center for NASA's flagship astronomical observatories, and a world-class astronomical research center. From 2018–24, Dr. Lotz served as the director of the Gemini Observatories, which are two 8.1-meter telescopes in Hawaii and Chile, on behalf of the National Science Foundation and the International Gemini partnerships. Dr. Lotz is an expert on extragalactic astrophysics and led the HST Frontier Fields work from 2012–2016 to study distant galaxy clusters and lensed galaxies.

Next to her, we have Dr. Matt Mountain. He's the current president of the Association of Universities for Research in Astronomy, AURA, which builds and operates telescopes and observatories for the National Science Foundation as well as NASA. Previously, he was the director of the Space Telescope Science Institute, and prior to that, he was responsible for the construction and also directed the Gemini Observatories. Dr. Mountain was also the telescope scientist for the James Webb Space Telescope. He received his PhD in astrophysics from the Imperial College of Science and Technology, University of London, and his research areas of focus include star formation, advanced infrared instrumentation, and capabilities of advanced telescopes.

Next to him is Dr. Chris Evans. Dr. Evans is the head of ESA of the office of STScI and the ESA project scientist for both Hubble and Webb. Prior to joining ESA in 2022, he worked at the U.K. Astronomy Technology Centre in Edinburgh for 16 years on the development of astronomical instrumentation where his roles included leading the U.K. R&D program for the European Extremely Large Telescope. While in Edinburgh, he also led a large international research consortium as the PI of a transformative ground-based survey of massive stars. Earlier, his career following his PhD at the University College London, he was a postdoctoral researcher at the Isaac Newton Group of Telescopes in Spain, okay.

And finally, we have—but not least, we have Dr. Olivia Lupie. She's the Hubble science instrument systems manager down at NASA Goddard, and that includes her role as one of the three operations managers for NASA's Hubble mission. She received her PhD in astrophysics from the University of Wisconsin-Madison. For her first 21 years out of school, Dr. Lupie worked at the Space Telescope Science Institute where she supported the orbital and science verification programs, instrument calibrations and its observatory-level characterizations, and operational initiatives, and was a member of the Wide Field Camera 3 instrument team from the onset. She then came to Goddard to work—and actually switched from working at the institute as an institute employee to working as a NASA civil servant. And she came over to work with the HST Mission Operations Team to experience a servicing mission, specifically Servicing Mission 4, from a unique and closer perspective. So, for over 20 years, she spent her time as a NASA civil servant.

So, what you're going to see here is three of the most senior people in terms of policy-making, managers, etc., in Jen, Matt, and Chris. And then Olivia is going to complement that from a different perspective, from a highly technical person who's been in the trenches with all the other workers dealing with the policies, working under these policies and partnerships in that, and she's going to give you her perspective of them from that.

All right, so let's start with the ESA partnership. A quick history is that back in around 1975, NASA was trying to sell this idea of a large telescope, and one of the problems, of course, was cost, and it was about half a billion dollars back then. There were people within NASA as well as Congress that didn't support having a project that was going to cost that much, so they said, you guys need to start thinking about some foreign partners. So, the first one that was mentioned was Russia because the Apollo-Soyuz mission had just occurred, but that was pretty quickly waved off because there was concern of technology transfer to the Russians. So then, they went to what would become the European Space Agency, and there was a decision made that they could support about 15 percent of the cost. That that would be the magic number, I guess, that would help sell the project through Congress and through the ranks of NASA. So that included both hardware, and support, and observatory time. All that type of thing was mixed into that, and that was approved in 1977. So, I'd like to start by first asking Chris if you could talk to us about what are the ESA contributions to the mission and how has it evolved over time?

Evans: Thanks, Jim. So, as Jim said, we're approaching the 50th anniversary of the signing of the MOU, which I think is remarkable. Half a century of working together on the mission, just 14 years ahead of the 36 years we're celebrating here. Within that MOU, so the contributions from ESA were threefold. So, the first was the provision of the Faint Object Camera, one of Hubble's first instruments, which gave us the first high-resolution UV and visible imaging from the observatory. And that was ultimately replaced with Advanced Camera for Surveys on the servicing mission in 2002. The second part is the provision of the first two sets of solar arrays. So, the first solar arrays were replaced on that, the first servicing mission we heard about yesterday in 1993, and then the second generation of arrays were replaced in '99. And then the third ongoing part is the support of science operations at the Science Operations Center, the STScI. And that's the provision of 13 people in support of the science operations and integrated into the institute, and that's the part which has evolved over time. I'm just talking to Olivia a little bit yesterday about this.

So initially, I think a lot of that team was in support of FOC, the Faint Object Camera, because that was the European contribution, and that was a mix, I think, of scientists and engineers. Now, we have astronomers as part of our support there, so, while doing their own research, and at the moment, they're matrixed across the mission in different areas. So currently, at the moment, in support of three instruments, so the ACS, COS, and STIS, as well as in the Science Policy Division and the Science Mission Office.

And another evolution has been, of course, ESA was a partner in JWST. A lot of the success of this partnership on HST fed into JWST. So, we also provide personnel in support of science operations on Webb as well. And anticipating this multi-mission stage, ESA and STScI in 2020 agreed to set up the ESA Office at STScI, which is a way of bringing together the ESA-funded team in one organizational unit, which has really helped with the integration, and from which the staff are matrixed into the institute, so—

Jeletic: I'm going to start with Jen for a second and ask, how is that implemented, that science support implemented at the institute? And how do you make decisions and things like that about where different people are and all that?

Lotz: It's really been fantastic to have such a strong set of scientists within the institute. Because of the long partnership, it's really very seamless now. I don't remember usually who's an ESA staff member and who's an AURA staff member. They're supporting all the instruments, of course. Historically, we've also had a member of ESA even be part of the Hubble Mission Office. So Helmut Jenkner was the deputy there for a long time, so senior leadership within the institute for Hubble, and then, of course, the Science Policies Group, which helps run the Hubble Time Allocation Committee.

That's really important to us to make sure that we have close ties to the European science community because of the expectation that the European science community will also be using Hubble. That also, I think, has been fairly seamless in that we never have to worry about whether

ESA is getting the appropriate share of Hubble time. It usually magically works out just about right. So, it's really been great, I think, also to have that broad perspective on where the science is going. Close ties to all the exciting activities that are happening in Europe, including the ESA missions, and, of course, the ground-based astronomy facilities there are amazing as well. So, there've been really excellent bridges by having these staff embedded at Space Telescope for many decades now.

Jeletic: All right, so if I recall, yeah, and I'm getting grayer, so there's many things that I don't recall correctly anymore. But it used to be that they were—actually ESA employees that came over and had a set period of time they had to be at the institute and then they would go back. And then that switched somewhere in there to now where they're hired by AURA or—?

Lotz: Right, we have a mix, so we do have staff like Chris and others who are truly ESA employees with offices in Baltimore, so a little outpost of ESA. But we also have staff that ESA provides funding for through AURA, and so they're AURA employees that's funded by ESA rather than by NASA.

Jeletic: Yeah, all right, and so, Matt, over the years, have there been any challenges to this arrangement? From your perspective, that there were any other changes or evolutions?

Mountain: It's always been a fantastic partnership, and like all partnerships, it goes through its ups and downs. And so, the Hubble partnership was fantastic, and ESA, at one point, decided that they may want—for JWST, they might want something specific, there will be a JWST office, but again, that became a debate. And so, things are as they are today, a very powerful partnership.

So like with all partners, there's always discussion, there are always disagreements, always agreements, but the sign of a true partnership is that you sit down together and go, "Well, actually, we think this is important," and we go, "Oh, we think this is important." And in the end, a real partnership is built where each partner recognizes what's important to the other partner and supports that. And ESA understood what was important for the leadership of the Space Telescope, and we understood what was important for ESA, for their view. And as you know, Jim, you've seen it over the years, it's been this very strong partnership. And like Jennifer, if I come to the institute—I happen to know that Chris works for ESA, right, because he runs all these things, but if you asked me to point out who worked for ESA and who worked for Space Telescope and who worked for—I actually couldn't tell you.

Evans: I think just to build on that. I've known STScI for a long time, but as a newcomer to the team, I think my impression from talking to people who were there earlier on, that integration has become more seamless and better over time. Where someone said to me, working together on the servicing missions was great, where people had a common goal, they were integrated in the same teams, and I think that was a real benefit. And similarly, when we've got that bridge to the European users on the Telescope Allocation Committee, on the user committee, I think the process is there for concurrence. And recruiting those members have also become a lot smoother and more effective with time, and it's that gradual evolution to something that's working very smoothly.

Mountain: There's a very important principle, which when a new head of ESA science comes in, you have to remind them, is that because it's integrated team the ESA scientists at the institute are not just serving the European community. Their job is to serve the entire community, and vice versa, the NASA-funded scientists are there to support everybody, and so there's this common purpose. On some of the ground-based systems, telescope time is divided. On ALMA, even on Gemini, the Canadians get their time, the Koreans get their time, and the U.S. gets their time. None of that is true at NASA or at Space Telescope, and I think that's very powerful. But it's reminding both sides, both the NASA side and the ESA side, I don't know and on JWST, the Canadian side, there's a shared mission to support the entire community, and that's actually a really powerful concept.

Jeletic: All right, so I'm going to turn to Olivia. And so we like to make lots of policies, and structure, and stuff like that, and then tell you how great it is, and then you have to live with it while you complain about us, although we never do that to [Pat?] [04:16:53], so trust me. But what was your perspective of this partnership, etc., when you were both working at the institute, at the lower-level technical side as well as at NASA?

Lupie: Yes, and that's a great question because from the technical perspective, right, there's always advantages for multinational teams, diverse teams. And it's said that you always get a better product when you have multinational and diverse teams, and that was tangible at the institute with our ESA colleagues. In particular, the FOC, I had a job where I was the most fortunate human being on the planet. I had a job where I had to interface with the PIs that built the instruments, like the PI of the FOC, Duccio Macchetto. I got to interface with the industry that built the instruments, for example, FOC, Dornier and Matra. I got to work with the engineers that were at the institute from these places, which was phenomenal that we had fundamental sources there.

The fantastic thing is at the institute, I, worker bee, had unfettered access to whoever I wanted, whoever we needed to talk to get the fundamental information we needed to do our jobs, our operational jobs, calibration jobs. And most certainly, the ESA colleagues and engineers that I worked with came with different perspectives, to the point where I'd say, "How the heck did you think of that?" And it really made our work much better. Especially for the FOC, I'm talking a lot about because I worked very closely with that team and with the engineers. So, the lesson learned there is management gave us unfettered access to the engineers who built the thing, to the PIs who designed the thing, and so forth, so that was great.

And then we had this, a whole different perspective from our ESA colleagues. I remember talking with Duccio Macchetto and Rodger Doxey, bless his soul, once. And the term, they didn't say it in this way, but fly as you test, test as you fly. That's visceral in everybody that worked on HST is you test as you fly, as you're going to operate the thing, and so forth. And I think Duccio Macchetto said that to me, and that was around, obviously, it was a NASA thing that they always had, but I always attribute that to Duccio Macchetto. And so, yeah, it was enriching and made the products better.

Jeletic: Okay, so I'm going to ask about one other part of the partnership, and that's the outreach side. Chris, if you could start by just quickly telling us how that partnership, when it comes to the coordination between both NASA and the institute with the Office of Public Outreach, on how that works, how you coordinate that, etc.?

Evans: Sure, so this is another example, I think, of in the past, there were some challenges just because of time zones and distance. And so now, we have an independent ESA/Hubble and Webb Outreach Team led by our team at the ESA Office at STScI. And we work, of course, very closely with the Office of Public Outreach at ST, and also with the team at Goddard, and here at HQ. And what this gives us the benefit of is being in the same time zone, we're in very close contact every day with the teams, both at OPO and at Goddard.

And so how this works in practice is if a result or a paper is led by a European team, we would typically lead the development of the science or image release. And there, we can emphasize the European contributions for our public and media in our member states. And then typically, the offices on this side will co-release those products to maximize the reach and spread the story and vice versa. So if there's a U.S.-led release, we would typically develop those and co-release that as well to enhance the visibility of the partnership there in the member states and, again, just reach the broadest audience as possible with all the inspiring results and the spectacular imaging as we heard yesterday.

We also work very closely—so we're independent of the main ESA science communications team who are based in Europe. They typically co-release our products, we're in regular contact with them, so we're that bridge between those two teams to try and bring everything together. And I think that just works very effectively because we're in the same time zone, in regular contact.

Lotz: I'll just add something here. I meet with Chris about every other week, and he invariably comes into my office with, "I've got something really cool to show you." He's always cheering me up with whatever the latest outreach is, either done in collaboration with the Space Telescope and Goddard teams or something that ESA has come up together. Truly a reminder of why we're here and why Hubble's so successful.

Jeletic: Okay, I think we're going to move on to the second major partnership, and that's between NASA and STScI. So, back in the mid-'70s, and this was mentioned a little bit yesterday, the National Academy of Sciences put together a team that did a study on how the science should be managed, the science program, and that should be managed for a large space telescope. It wasn't named Hubble yet at the time. And so, they came up and put the results in what was known as the Hornig Report, okay. And one of the major findings in that report, recommendations, was that there will be an independent institute that does the science operations side of things. So, there was a procurement that was put out, I think there were three bidders, if I remember correctly, at the time. And AURA won that bid, and so they've had a contract since 1981 to partner with NASA and provide various capabilities, so. So, I think I'd like to start with Jen, and if you could just expand on what you see as the major roles of the institute over the years and the relationship with NASA?

Lotz: Sure, the Hornig Report's really interesting, and I go back and read it every so often. And it's amazing how much was seen in that report, which was actually a recommendation from the National Academies, and how well we have managed to achieve those goals. I think when that report came out, the scientific community and NASA knew that Hubble was going to be serviced. They knew it was going to be a flagship like no other space telescope, and it was something that would be around for decades. So, they were really worried about or really thoughtful about how do you support the scientific endeavor over the long term.

And so that ethos, that mission is something that is at the true core of what space telescope is all about, our values, is to make sure that the science comes first. And one of the most important ways of doing that is having scientists who are actively using the telescope, who are trying to answer their own very difficult scientific questions working in close partnership with engineers, with the flight ops team at Goddard, with folks across the broad partnership to make a truly scientifically exciting, on-the-cutting-edge observatory. And so that comes out in a number of different ways. I think Hubble was one of the first, probably the first to have data in archives that was then publicly accessible. And we've seen now the legacy of having exquisite data in these archives for decades opens up brand-new science that you could not have done the first two years of that data. But when you look back at something over many, many years, you start to make truly amazing discoveries.

We were the first to have funding come with observing programs. So scientists within the U.S. can use that funding and fully support their students and postdocs. They don't have to worry so much about having double jeopardy of, okay, I've got all this great Hubble time, but how am I going to pay students to work on it? It comes through making sure that that data really is at a high standard, uniformly calibrated, you know what you get. Folks don't have to spend a lot of time devising their own calibration program or working it out; they can get straight to the science.

And then it comes through innovation. So even though the telescope is 36 years old, maybe you want to go back to the last servicing mission, which was in 2009 when we replaced the instruments, so it's not really 36 years old. That's, what, 16, 17 years old. There have actually been innovations through clever engineering tricks of new ways of using Hubble, both with new instrument modes, which is pretty amazing. Doing ways of using the Wide Field Camera in which you're scanning the sky, and you get a lot of data quite quickly is one example. I think the fact that we were able to move to reduced gyro mode in the last two years, operating Hubble most of the time on a single gyro with almost no impact to scientific quality just speaks to the amazing creativity that you have. When you've got scientists with a goal, make sure you protect the scientific quality, working closely with engineers in this partnership with the institute, with Goddard, with ESA.

Jeletic: Matt, I'm going to ask you, as previous director and head of AURA, any other thoughts you have on that?

Mountain: There was also a very important philosophical shift with the science. So big facilities in particle physics and small emissions, the people who've got access to those facilities had to join a team. So in particle physics or in some ground-based programs, if you wanted the data and you wanted to have access and write papers, you had to join a team.

And it was actually the first director of the Space Telescope Science Institute, Riccardo Giacconi, who came from a very elite institution, who made the statement, this is a federal investment in science, how do we maximize the science? We maximize the science by maximizing participation. So, the mission really was to democratize the science, to create an institution where you didn't have to be a black belt X-ray astronomer, or radio astronomer, or optical astronomer to use this very complicated telescope, HST. There was the skill of people, scientists who had made a commitment to help the community use the telescope. It wasn't just the people who built it.

In fact, Hubble and all the software the institute built is actually built for others, not for them. And that mindset change into what's called the Great Observatory Model is why you have a community of 23—you have 23,000 papers and 10,000 people across the planet who can use it. And, of course, they've taken it even further by dual-anonymous review. And the peer review, the community sees the peer review as being run by scientists that they know, the community. And the National Academy of Sciences has occasionally delved in, is this a good peer review? And it has survived constant review in of itself because it's a trusted peer review because they can see members of their field participating in that. And that trust that the partnership with NASA and the institute has created is unique and powerful.

And the European Southern Observatory has adopted the same model. Of course, we've been using it on the ground, but NASA really took it to a new level because they funded grants with it. They made sure that everybody could—the documentation, created products that could—long-living archives, and that is a completely unique model. Because whether you're an astronomer at Caltech, or Wisconsin, or a small college in Vermont, you can do great science because you can access the Hubble as a peer with everybody else. What you need is a great scientific idea, and that partnership is what's incredibly powerful and very new.

Jeletic: Okay, so I'm going to ask Chris, from the European perspective, how do you guys see the partnership between NASA and the institute?

Evans: So, I think in terms of just thinking about how we serve the community with the best data products. We heard a lot yesterday about the archives, and so I know one of the challenges in the past was how do we coordinate the data access on the European side and in the U.S. And so previously, the European data access was through the Space Telescope European Coordinating Facility at ESA in Germany. And I think earlier on, a lot of the challenge was the physical media as well as the distance. And that led to people being unsure of which the best version of the data were, where to cite, the synchronization of the data. And in the middle of the last decade, the decision was made to consolidate all the data processing and hosting at the institute, and then we have a mirror archive in Europe, and there's now a mirror archive in Canada.

And I think there, that's a good example of how do we serve the best products to the community around the world alongside the different datasets. And that's making the most out of the mission for NASA, for the institute, and for our European user community as well. Alongside other ESA missions, you get different synergies there, but also on the U.S. side where MAST hosts the data for many missions. So, there's a strong partnership there between the other NASA missions and the institute that we can then feed over to the European users as well.

Jeletic: All right, Olivia, it's your chance now. So, you get to say it from both perspectives. When you were at the institute, how did you see that NASA-institute relationship, and now that you've been at NASA for 20 years, how do you see that NASA-institute relationship?

Lupie: Okay, at the technical level, the relationship with NASA—well, let me talk as an institute person. I started out at the institute in 1983, and so, again, like I said before, the nature of my job and many others was to collaborate with or interface with so many different disciplines and so many different types of industry, and so forth, so. So, when I was at the institute, I also collaborated with my compatriots on the mission team at Goddard, and at the technical level, there was no problem at all. We felt like we were all one team, and again, it was badgeless, institute or NASA, it was completely badgeless. I give the institute a lot of wonderful credit, the management, again, who always wanted us to interface with mission operations. You have to do that.

The other thing that was really important, I thought, between NASA and the institute was when we were building the instruments, the original instruments and then the new instruments that we installed in servicing missions. One of the most important things that I believe is one of the reasons why we have such a long mission, a longevity on Hubble, is that your engineers and scientists are embedded in the teams that are building the thing and testing the thing, right? And so, for example, our operations systems engineers, right, they were heavily involved in writing the procedures that were used during testing. The goal here was not to leave operations. We'll design it, and we'll put all of these great things in, and then we'll worry about operations later. That's not how Hubble worked, nor does it work that way now. It's you look at how are you going to operate this thing on orbit initially, even when you're building the instrument. And that has proven time and time again to be terrific. So, I don't remember what I was going to say. Yeah, and so the badgeless nature of it, and the fact that you didn't have to worry about hierarchy, management hierarchy, right? We could call up Goddard from the institute if we needed somebody.

And now when I'm in the opposite, now I'm at NASA on the Mission Operations Team, we love working with the institute instrument scientists, every one of us. And I'm an astronomer, right, so it's maybe natural for me to want to optimize science. Like Matt said, optimize the science Hubble gets, to optimize the time. But our engineers all along here since I started, they feel the same way, and they're driven to save every photon, right? The instrument scientists know this because they've been in meetings with us and so forth. But even engineers who are not in the field have always had that mindset, is we want to optimize science, we want to get Hubble back as quickly as possible if we had an anomaly, and that's what drives everyone. And that philosophy was at the institute and promoted at the institute, and that same philosophy was at the teams at Goddard.

Jeletic: Okay, so I think there's one other part of the partnership, and I'm going to direct this one to Matt, because Matt would be at the institute around this time. Now, I know that you started right after the cancellation of Servicing Mission 4, but there clearly was a partnership that occurred between NASA, the project, and the institute with that cancellation. Do you have any insight that you would like to reflect upon with regard to what happened back then?

Mountain: Well, I can't get in trouble because I arrived after that all happened. One of the advantages that the institute has is that it sits on the Johns Hopkins campus, and so it fits within the environment of Johns Hopkins, within the larger political environment of Maryland and the nation. And so, the people at the institute can actually talk to stakeholders in a way that NASA civil servants can't. And so, when that mission was first canceled, as well as members in this room played a part, there was a broad advocacy campaign to try and restate Hubble and put it back, and it was very successful. And we had schoolchildren sending in their pocket money to save Hubble. And that partnership with other stakeholders in the broad political environment is something very unique that the institute brings to the Goddard Space Flight Center. It's only really matched with what JPL has because they have Caltech. And so that's what has enabled some longevity, so that collaboration has been very, very powerful.

And, in fact, I remember when Mike Griffin was appointed administrator, well, his second or third calls was to call us up and say, "Okay, we're going back, what do we do?" That is a very powerful partnership that I think is carefully stewarded to make sure that everybody knows what their respective roles are, but it makes why—look, Hubble is the most productive telescope humanity has ever built by factors of several. How did that happen? Why is it so powerful? People compare us to other telescopes and other things but just look at the scale which Hubble has succeeded. Twenty-three thousand papers, a community of 10,000 across the planet. No other telescope has that reach and that power, and that is a unique NASA-institute community political partnership that has created that incredibly powerful science machine.

Jeletic: Okay, so I'd like to go to the next group of partnerships, so outside the big two, I'll call them. So, there's a lot of other things that we do that clearly, without any question, increase the amount of science that's returned for the agency. And so, I want to just go through a couple of those first, and then there are some other ones that we may not think of as partnerships, but they're clearly there.

So, the first was we have had partnerships for archives in the past as well. There was one with the Canadian Space Agency if I remember, and I thought there was one with Japan for a while. And, again, these partnerships were outside of NASA, so there wasn't a formal MOU or anything. I think the Japan one was a cost-reimbursable arrangement, but with the Canadians, it was we kept pushing data to them on a periodic basis, so they had their own copy of the archive. Do I remember that correctly? Does anybody remember? Okay, so I'm showing my gray hair, which is fine.

Jeletic: Okay, all right. Another one, though, that we have right now, and you'll see that in the call for proposals for every cycle, etc., is that there is clearly a partnership that has been created through the institute with other space-based and ground-based observatories. I'll just start with you, Jen, to say if you can elaborate on how those—the ones that exist today and how they came to be and all that?

Lotz: Yeah, when we offer Hubble time to the community, we also offer the opportunity for joint observations, and actually that goes both ways. So Chandra, for example, will also have the opportunity to offer Hubble time. This is really a useful way for scientists that are thinking about multi-wavelength or very complicated programs to make sure that they get all the pieces of the data in one go with one proposal, right, again, trying to eliminate the double jeopardy. And what we found is Hubble's fantastic. It's something that astronomers absolutely are publishing with only Hubble data. But often, the questions that you ask about how does star formation work, what's going on with this exoplanet system, what's happening in the time-domain astronomy realm, these are questions where astronomers use every tool available to them, they don't stick to just one telescope. And so, recognizing, again, the need to put the science first has enabled these cross-observatory partnerships.

As you were talking, Jim, I was also reminded of when I was a graduate student and postdoc was truly the era of Great Observatories. With Hubble at full blast, we had Chandra operating, we had Spitzer operating, and there were a number of amazing programs in that era that used large datasets from all three of NASA's great flagships that were available at the time. And that has left an incredible legacy. And if you look at what James Webb is doing now, they're going back and revisiting those fields, they're pushing them to the next level. I think it's important to think not just of Hubble's one-off partnerships, but really that suite of NASA facilities or suite of available facilities around the world being used in partnership to answer the big scientific questions of the day.

I'll just end with also saying that at Space Telescope, I have the opportunity not just to see Hubble's science operations, but it's also James Webb and Roman. And we try to make sure that the community is thinking about using those things in partnerships, and there are opportunities to do that. So, we've had Roman preparatory science calls for Hubble, and the community is using Hubble data to get ready for Roman in the way that they also used Hubble to get ready for Webb.

Mountain: There's one other partnership that Jennifer must take a lot of credit for. There's a partnership with theoreticians. They are a different breed out there. When Jennifer was doing the Frontier Fields, one of the issues was how do the lensing models with dark matter work? There were lots of groups that had their own bespoke way of calculating what a lensing model was like. And Jennifer decided that she was going to try and bring all these warring groups together, and have theoreticians, and gave them small grants that NASA allowed us to do with the Frontier Fields. And it was actually a very powerful partnership between the theoreticians. They all had to work on the same cluster and come up with the same answer, which they'd never done before.

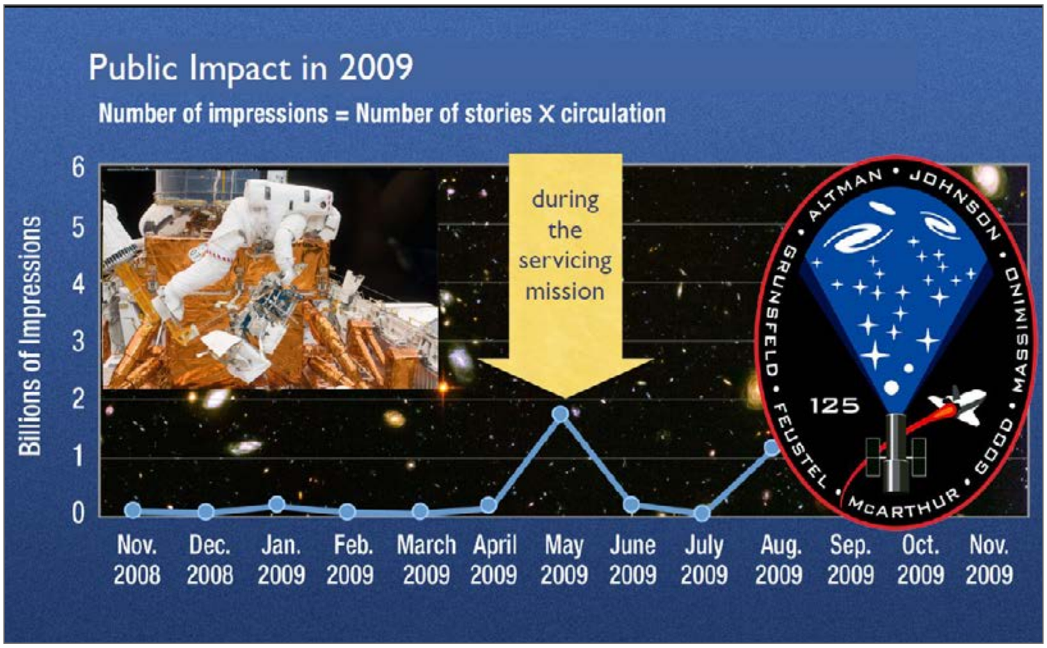
And at the summation conference that you were at, it was very powerful to see theoreticians and observers really working together to understand things. And I think that's also the convening power that a place like the institute has. Because it has one foot in NASA and one foot in the academic community, gives the institute a unique convening power where people feel safe to come, and disagree, and to talk as an academic and a theoretician. So that was a very successful partnership as well.

Jeletic: All right, well, I'm going to stick with you, Matt, and say that—so there are some other partnerships that people don't really think of as partnerships, but they are. So, I wanted to just point over towards you, and if you wanted to mention about the U.S. and international public?

Mountain: Well, I think there's the two partnerships we haven't talked about. There's the partnership with exploration. How many times have we been back to Hubble? That was One NASA, five servicing missions, without the partnership with human exploration, without those early days. I was new to all of this, a lot of you had been through several of these, but it resonates with what Len said, there are no heroes. There are these great teams of human spaceflight, the science committee, Goddard, Marshall, Johnson. You remember all those meetings we used to have.

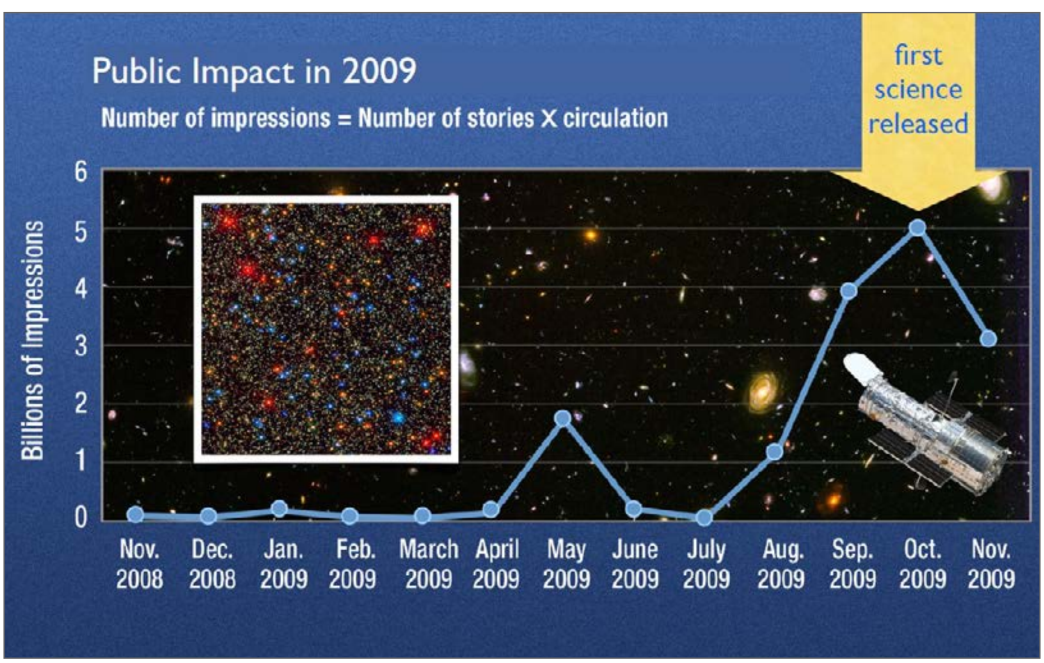
Jeletic: Mm-hmm.

Mountain: And that created these incredible servicing missions, which is why Hubble is the most productive telescope in history, but there's another partnership. Can we show my first slide?



Jeletic: Yeah.

Mountain: There's a partnership with the public. So, this was a remarkable chart that I saw. This is a chart of the public interest measured by an advertising company. It's a metric as you know. It's basically on the y-axis is the number of stories that were written in the press, online and in traditional press, times the circulation, and so it's measured in billions. And not since the accidents had NASA seen such an impact of a shuttle mission. This is the astronauts going up in SM4, two billion impressions, which was mind-blowing at the time, wow, what a lot of interest.



What took all our breath away is the next slide. That's the interest that was generated by the science coming out. The public is fascinated by the science these missions produce, uniquely so. The science really drives the interest, and I think that's an important message for everybody. And this science comes at a steady cadence that people, that NASA can use to fill those deserts and in between the Human Spaceflight program when things aren't happening. The public really wants to see the science coming out, and it has more impact than even the launch and astronauts rescuing these things. And those of us on James Webb, James over there, the same effect was seen at James Webb. Huge interest in the launch, and then four or five times more interest when the science came out.

So, the fact that people could be heard talking in bars in West Virginia about, "Did you see those results?" Many of you have been in taxi cabs, and people have asked about, "Oh, you're with the Hubble?" The most fascinating thing that many moons ago, John Grunsfeld, if he's online, dragged me to go with him to Bangkok, in the middle of the riots in Bangkok to give a talk on Hubble and James Webb. I was doing the James Webb, it was new, and he was doing Hubble. And we went in in black cars into this place in the university at Bangkok. There were four lecture theaters full of people all there to listen. And John Grunsfeld said, "And by the way, you can get all these images on the web." Everybody raised their smartphone in the whole audience.

We were given a little tour of a temple. When they heard that the people who ran the Hubble were coming, all the people who worked at the temple wanted to line up and meet John Grunsfeld. And the ambassador told us that Hubble had generated more interest than actually the visit of President Obama at the time. The soft power of the impact of Hubble and now the James Webb needs to be remembered.

Many years ago, I had to give a talk at the University of Oxford, and I think I was talking about James Webb and the Hubble. And this gray-head guy came up to me afterwards and said, "I was the last ambassador to Hong Kong, and I want to tell you, and please pass this on to NASA, China is deeply envious of your Hubble Space Telescope because of the public impact it has generated globally and the brand that NASA carries with these missions." Because as you can see from here, the interest just continues. And that partnership with the public, particularly the public in the United States, is also what contributes to the longevity of it. Public support generates political support generates continued support for science. And it fills you with wonder, and awe, and gratitude that the American public is willing to invest in our observatories as long as we return the data to them, which NASA has traditionally always done. That partnership with the American public and the global public is key to the success of missions like Hubble, the James Webb, Roman, and obviously Habitable Worlds.

Jeletic: So, yesterday, there were some conversations about the impact that the images have on the public and things like that, and again for Hubble, I think that there's no bad to that. It's only good. It's great public affairs with the general public. So, I'm going to give you a couple of statistics that just reimburse what Matt has said, and they're from today, right? So even after 36 years in orbit, and all the observations, and a lot of other new, Great Observatories and that, the senior level of NASA, in terms of the communications area and that, get it. One out of every five and a half posts on the NASA Instagram account is an image that has Hubble data in it, right. So sometimes they're just

Hubble, sometimes they're Hubble and Webb together, sometimes Hubble and Chandra, etc. One out of every six and a half images of the day for NASA is a Hubble image.

And then there's a newsletter that goes out, it has over 5 million subscribers, and it's a weekly newsletter. It goes out on Friday on Hubble Science—I'm sorry, on NASA Science, NASA Human Space Flight, anything that's NASA related, and we're in, we have an article basically every other week, so NASA gets it. We're also, at least once a quarter or more, the banner image on the NASA landing page. So, I think that there's only pluses that can come from us continuing to do those types of things, putting out the images, putting out the science releases in that because I think the public really resonates with it.

Okay, so what I'm going to do is I'm going to ask two questions, and I'm going to let you guys pick which one you want to answer, okay, as a quick way to start closing this out. I'm going to say that since Hubble's going to be operating for another 35 years, okay, returning great science and discoveries and that, what changes, or new partnerships, or anything like that would you be recommending for us, as well as for somebody like the Habitable Worlds Observatory? This is the second question you can choose to answer, or you can choose both, what's a top takeaway as far as the partnerships are concerned that you would want to relay to them? So, I will start with Chris.

Evans: I'll take the second one on those.

Jeletic: Okay.

Evans: So, in terms of thinking about what's worked so well and you could apply in the future, so I think, for me, the key is the integration of the team at the operations center. I think that's very effective, then you can be the bridge to your user community, but you're there. It's immediate. When issues arise, you can keep the communication going very strongly, I think that's been very effective over time. And as you're talking about if you're looking forward to the future of Hubble as well, it's that long-standing, international collaboration, which then builds up over the different missions. So, I think the overall overarching benefit from Hubble over the decades has been we've got a very interwoven science community now, very strong collaborations to bring those different expertise to solve the science issues we're addressing with Hubble, and we'll continue to do so into the 2030s.

So, in Europe, we've got a very strong and engaged user community of over a thousand people, uniquely CO-Is in the last cycle, and I did a bit of digging over the weekend. So in the last cycle, in the 30 programs that were led by European PIs, over two-thirds of those had CO-Is in the U.S., so there's a very organic interplay here of the science teams. And as people were saying yesterday, then bring different multiwavelength data from other observatories to address those topics from ground-based observatories, from other space missions as well. And I think it's just that very organic building up over time of working together as one scientific community to address those questions that you could then build on for future missions hopefully.

Jeletic: Olivia?

Lupie: I thought this was going to be the free-for-all question. I'm going to take it down a little bit again and just say, on a technical level, the partnerships that we have with the institute in terms of the instrument scientists, our project scientists from NASA who are a bridge also to the institute and to the community. All of that, again, is responsible for or is partly responsible for why Hubble has been so successful and has lasted so long. So as long as the institute, and ESA, and Goddard emphasize the importance of collaboration, and of no badges, and of each person has ownership. Even the public feels that they own part of Hubble or that they're responsible for Hubble in some way. Giving the technical teams that kind of mindset, you get dedication and devotion, and you're able to operate this thing and optimize science with smaller and smaller teams, although that can be a problem, but too small is not good. And we have the instrument team lead of the Wide Field Camera 3 along with my esteemed colleagues, and Pat Crouse, and James Webb lead, and Roman. And they all contribute, and they all feel like they own not only Hubble but these other missions.

So, I won't continue to go on, but just say my career, which is a 43-year career on Hubble, I still get choked up when I see the smooth and sincere collaborations between technical and science. And anyway, if we can just keep that up and make sure that happens on the other missions, then we're doing really, really well.

Jeletic: Jen?

Lotz: I'm going to pick something a little different, which is I think Hubble needs to continue to support the next generation of astronomers. A third of our proposals every year out of the 800, 900 proposals that we get and then a third that are awarded are from folks that have never used Hubble before as PIs, right. And as we look to the future, what Hubble will be doing in the 2030s, it's not that we want Hubble to just keep doing the same old thing. We need to understand that the landscape is changing, that scientific questions are changing. When Hubble was conceived of, folks had never seen an exoplanet, and now, it is a critical part of our understanding of whether exoplanets can keep atmospheres, which of course are a critical piece to whether those planets can have life on them.

So, we've just actually asked for a call for white papers from the community to see what are the ideas and what science questions Hubble should be answering in the 2030s, knowing that Roman's coming online, knowing that there are other UV-capable observatories, but also knowing that Hubble retains some truly unique scientific abilities that no other telescope will have until Habitable Worlds flies. And I think Hubble has a really important role to play both in answering truly fundamental, scientific questions that no other observatory will be able to answer until we have the next UV optical flagship. As well as supporting the next generation of scientists that are going to be needed to be leading that next generation of NASA flagships.

Jeletic: Okay, Matt?

Mountain: I'm just going to go off what Robert Smith said at the beginning. What does it take to succeed at these great missions that are civilization changing, like Hubble, that we believe the Webb is going to become, that we think Roman will become, and we hope Habitable Worlds become?

If Habitable Worlds discovers for the first time in human history, we're not alone, that won't be a moment in history that is forgotten. What does it take to get there?

And the partnerships that are being created with the Hubble, with ESA, with NASA, with the public, with the political establishment, with the institutions, with the universities, those continuous partnerships. The work we all have to put in to make all those partnerships work is incredibly powerful. And I have to thank Robert, he said you have to advocate again and again and again, and we saw this. We forgot about that when James Webb ran into trouble, and it ran into trouble, and we had to wake up again and remind ourselves that we had stopped telling the story of the James Webb Space Telescope. And so, we started retelling that story again to everybody, to the public, to everybody who would listen.

And what NASA does better than any other agency on the planet is create these amazing observatories because they allow and enable these partnerships to flourish. They accept that they're abroad and that the NASA Center can do one thing, and institute can do another, that universities have another role, industry has a role. That whole broad partnership is unique to the American experience and to NASA's experience. And so, let's not lose that because that partnership, that broad coalition building, that broad support for the excitement—

If you think about this for a moment, the Department of Energy is designed to defend us, NIH is designed to heal us, what's NASA for? It's actually designed to inspire us, and inspiration can come from great science as you see from plots like this, and the wonder that we heard about the images, and the feeling of emotion. That emotional connection to the science is that NASA has allowed everybody to enable that. They have supported great outreach. They have supported great advocacy, great engineers, great partnerships. That is how we build the future science.

Jeletic: Okay, all right, what I'd like to do now is open up a question-and-answer session. And if anybody has any other things they'd like to ask us or state, you're welcome to do that as well.

Audience Member 4: All right. Thanks very much, it's really inspirational, and I have experienced what you-all have said, which is that walking around the Space Telescope Science Institute, I don't know who's badged, mostly, to STScI or to AURA and who's badged to ESA. It's been wonderful, especially during this long operations phase for Hubble. It's a little different when you have a partnership in a development phase where one entity says, "I'm going to build this instrument," and they do it, and they provide it, and it's done. This is an ongoing partnership throughout the operations phase.

My question is, looking at potential, future, or other NASA partnerships, is there a risk in this in the sense that we depend, NASA depends, STScI depends on the ESA partners to be an integral part of your success as instrument scientists and other roles there? What if ESA decided to just pull out for whatever reason, would that leave the functional capabilities of the missions in a lurch there? So, is there any risk in this model of operations where you are dependent on the contributions of another space agency, in-kind, in-person type of expertise? Is there any risk inherent in that, or is this just a perfect model for all kinds of missions in the future?

Lotz: Yeah, I guess I'll take that one. Yes and no, right? I think having that strong partnership with ESA, that strong connection to the European community and the global community makes

Hubble stronger, makes the operations better, makes NASA stronger in its ability to achieve its objectives. I would say after 36 years, we're looking at all kinds of potential disruptions across the board, and personally, I'm very grateful for the very steady partnership and reassurance that I've gotten from NASA, and I want to acknowledge that—or sorry, from ESA, I'm so sorry. ESA's been an incredible partner here, and it would be truly detrimental if they walked away. But I think, like everything, we would adapt as we've all been forced to adapt in ways, but fortunately, that does not appear to be a risk at the moment.

Evans: Echo on that, when our director of science has said, "We'll continue to be the trusted, steady partner." As I mentioned, we've got a very large user base on Hubble, we've got an even larger base on Webb, so I think the engagement of our user community is they get a fantastic science return out of this with these strong international connections. And I think we will continue to make the case to carry on for as long as NASA is leading.

Mountain: Let's not forget that partnerships are actually hard work, but it's worth the work, but it's always hard work. There have been deep disagreements between ESA and NASA, even at the institute, but those get worked out because they're partners. So, it's never easy, but the work is always worth it, and when it works well, it's fantastic. And then there are times when we disagree, and there are lots of partnerships. There are partnerships with human spaceflight, there are partnerships with different parts of NASA, there are partnerships—nobody said building Great Observatories was going to be an easy job.

Jeletic: Okay, Julie?

Julie Crooke: Hello, I truly believe in addition to Hubble being an amazing facility and observatory, a lot of its longevity is due to the servicing emissions, which was enabled by the low-Earth orbit, and shuttle, and astronauts, and so forth. And my question for you, I've been told that both JWST and Roman were, "at the point where HW is now in terms of thinking about robotic servicing." And I know there are some skeptical people, I am not one of them, but I also am trying to figure out ways that could—how do we break the paradigm of, okay, obviously, HW is going to be at L2, and how do we get the mindset, and too, could do—? I'm curious how you-all feel about, is it more likely to engage with the human side again with NASA or really rely on industry, which truly does have the potential? Anyway, I would love to hear your thoughts on how to bridge the gap to enable these observatories to continue to last in the wave of these mountaintop observatories that can really keep going and producing even more amazing science, as Hubble has done.

Mountain: Well, Julie, I think the important thing to realize that what enabled Hubble servicing wasn't just NASA, it wasn't just industry, it was all of the above. And I think the person who said we should service Hubble that's just walked in, Mark Clampin, because he saw the potential of what servicing has done for Hubble. And I think that if we're going to build a telescope on a mountaintop somewhere out at L2 or wherever we're going to do it, it's a powerful metaphor for the future of NASA. If we're going to go beyond the Moon, go to Mars, aren't we supposed to be able to robotically service out at least a million miles out to L2? It's a little bit further to Mars.

Julie: Yeah, I totally agree. I guess where I'm getting at is when NASA was able to leverage, as Ed Weiler used to say, OPM, other people's money, on the human side of NASA, there's a real fear within NASA to—well, I shouldn't say all of NASA, but certain sectors—that the Science Mission Directorate or even just the Astrophysics Division can't pay for a servicing vehicle per se. And so, we're just trying to strategize on how to bridge a path or multiple paths, parallel paths to—I'm planning to engage with the Artemis program, but they took away Gateway, and it's surface only right now and—anyway. So, I'd just love to hear your thoughts on the best path forward for—well, how we get to that.

Mountain: I don't often say this, but this is way above my pay grade.

Jeletic: Mark?

Mark: Hi, so one partnership that hasn't been discussed today yet is private-funding philanthropy. And in other sciences, like in biology, the Allen Institute, the brain institute, the cell institute have really made a huge difference for that science area. And we now have new money in astronomy as well with Schmidt Sciences. And I'm wondering, how do we move forward to best leverage that and get the best science through those partnerships?

Lotz: Yeah, I think what Schmidt Observatories is planning to do is really interesting and really potentially quite exciting for how we should be thinking about space science and space observatories going into the future and astronomy in general. I think it's clear, there are things that they want to do and will try to do, and there are areas where they feel that federal government should be leading in these areas, right? Philanthropy does not replace NASA's budget by any means. So, figuring out what's the right area where a group like Schmidt can really push the envelope and do something that is hard to do in a federally funded landscape absolutely is the right thing for them to be doing. And then understanding what lessons NASA-funded or federally funded space entities can take from that.

I think one of the things that's really exciting about what they're doing with those really is pushing the envelope on the coronagraph, right? It's not a replacement for the things we hope we can do with Habitable Worlds, but it's certainly a step in the right direction, taking the next step after the things that Hubble has done, the things that Webb has done, and the things that Roman will do. That's the potential to learn from a really difficult technology that, hopefully, we can incorporate into the next generation that NASA is doing.

Jeletic: Heidi?

Hammel: Another partnership that really hasn't been discussed much, although Matt, you've mentioned it once or twice, is partnerships with industry, and how important they can be. And I know that from a JWST perspective, but I really don't know much about it from a Hubble perspective. So, I wonder if some of you could talk about that, and also, Chris, in terms of industry in Europe and how that may have helped support Hubble instrumentation? I honestly don't know. So, is there an industry partnership for Hubble that might be worth talking about?

Evans: I mean, there's a very explicit partnership with Ball Aerospace, now British Aerospace Systems, that built many of the instruments on the last servicing mission. That was an ongoing partnership, and that built up over the years, and you saw that partnership carry on into the James Webb Space Telescope. So industry, at least, that's my own experience. I mean, there must have been early partnerships with Lockheed Martin, they're very proud of the Hubble Space Telescope, and we know that Northrop Grumman is very proud of what it did on James Webb. So those partnerships are there, we don't always explicitly acknowledge them, but they are real, and there are people who really contribute but—yeah.

Jeletic: We definitely like to think of Lockheed Martin as the contract, right, but Lockheed Martin really bends over backwards for us. I mean, they want to see success. All their employees have great pride in Hubble, and they want to make sure it's working, they want to make sure it returns as much science as possible in that. And they go out of their way for us many times, in terms of especially when we need reach back for expertise in that, so many of us consider them our partner.

Hammel: Just a follow-up, and, Chris, I do want to let you share your thoughts about European industry. But not only what they do for the mission, but what they can do for the mission beyond just build an instrument, it might be worth touching on that.

Mountain: Are you talking about industrial coalition? Yeah, I mean, industry was a key advocacy partner during the James Webb period, and I think let's not underestimate what they can do if they focus on the same objectives as we do. But I think there's another important aspect. You used the word, they're a contract, but we like them anyway. In any good relationship, there's the contracting relationship along one axis, but then there's a partnership axis on the other, and the best outcome is when you have both. You can be a partner and a contractor, acknowledging who your customer is, but also acknowledging what a partnership is, and that's where Ball was very good and is very good.

Jeletic: All right, I think our time is just about up, so I'd like to thank the panelists for participating today.

Session Five

Hubble's Empowerment of Current and Future Astronomy Missions

Moderator

Shawn Domagal-Goldman, NASA

Panelists

Mark Clampin, NASA
Julie McEnery, NASA
Giada Arney, NASA
Knicole Colon, NASA
Jane Rigby, NASA

Domagal-Goldman: Good morning, everybody. I think this is our final panel of the Hubble Symposium this year, so I'm really, really happy to be here. We've got a great panel in front of you to talk about flagships from Hubble going all the way to what we have operating today, into the near future, and a little bit further into the future. For those who don't know me, I'm Shawn Domagal-Goldman, I am the director of the Astrophysics Division here at NASA Headquarters.

I'm going to take a moment to introduce the rest of our panelists moving from the closest to me across the stage. We have Knicole Colon who's the Webb operations project scientist at NASA Goddard Space Flight Center, Mark Clampin who's my predecessor in this position and is currently the deputy associate administrator for NASA Science Mission Directorate, Jane Rigby, who's the Webb senior project scientist at NASA Goddard Space Flight Center. Giada Arney, who is the Habitable Worlds Observatory project scientist at NASA Goddard Space Flight Center, and Julie

McEnery who's the Roman senior project scientist at NASA Goddard Space Flight Center. I'm really glad you all are here.

I'm going to jump right in. Does anyone want to give an opening comment or anything, or do you want to jump right into the fun stuff and the images?

Domagal-Goldman: Well, it's going to be choose your own adventure. I want to start with a question for all the panelists, which is the fun stuff I just alluded to, do you have a favorite science image from one of our flagships? Why is it one of your favorites? For the folks in the back, do we have the—be able to display? We're going to go forward with these. I'm going to start, Mark, with you, did you have one you wanted to highlight?

Clampin: Favorite image?

Domagal-Goldman: Favorite image.

Clampin: So, I'll actually go with a Hubble image and go with the Ultra-Deep Field image that we took with Advanced Camera. And it's partly my favorite image because I built the arrays with Ball Aerospace and a company called SITe. So, it's still, I think, the deepest visible image of the universe, so that's mine.

Domagal-Goldman: Wonderful, Jane, how about you? I'm told I'm in control of getting the images on there, but I'm not successful thus far, it's been that kind of day for me, but go ahead. Jane, you go ahead, and I'll see if I can get it up there.

Rigby: If you can get it up? Okay, I picked a Hubble image and a Webb image. The Hubble image is of a lensed galaxy, RCS 0327, which is one that's a little personal. I picked personal choices; otherwise, it looks like I'm showing favorites. That's one that we proposed multiple cycles with Hubble for and finally got. It's the brightest lensed galaxy in the sky, it's incredibly bright, and so you can just do illegal things with it. And so, we were able to demonstrate spectroscopy that had never been done before, those redshifts that now is so utterly routine with Webb that the kids are like, "Ah, of course." But it was like a little bit of getting to see in the future, and so the Hubble image was the first that unlocked being able to get a good lensed model using the techniques that we were talking about from Frontier Fields.

And then the other image is actually probably the ugliest one in the slide deck and is the first image of a focused star that we released with Webb. And that one's just personally really special because that was the night that we knew that not only was the telescope working and taking sharp images, but it was working extremely well. Because around that star were thousands of galaxies that just popped out everywhere, and so that was the, oh my goodness, every field is a Deep Field when you have a telescope this big. And we were cautious enough in the release image that we set the contrast such that a lot of those galaxies are in the black background. And then the community took the JPEGs and messed with the stretch. It's like, oh my God, there are galaxies everywhere. Like, yeah, it was the first indication that Webb was going to be technically absolutely transformative.

Domagal-Goldman: Love that. Knicole, how about you?

Colon: Sure, great, so we have some images here, and I had picked the one that's showing on the screen. This is known as the cosmic tornado, it's a Webb image, and there was one shown, if you had seen quickly, of a smiling, happy face. That was a Hubble image. Yes, this one, which is showing also lensing. And I picked these two examples because you think of tornado, happy face, these are things that we can relate to on a human level as we're trying to explain on astronomical scales, both the size of the universe, but also scientifically, the connections between star formation in the cosmic tornado, galaxy evolution in this happy face. It's connecting things that we can relate to, but also magnifying the importance of the science that both Hubble and Webb can offer. So, I really enjoy these fun, cutesy images, but that are just rich of information as well.

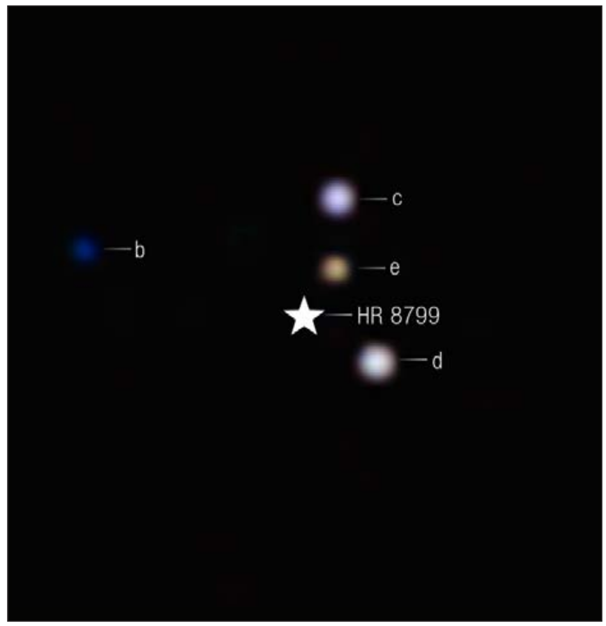
Domagal-Goldman: Thanks, Knicole. Julie, how about you, what's your favorite or what is a favorite?

McEnery: So, I picked the Crab Nebula because I think it's such a great story. If you think of astronomy as starting over a thousand years ago, astronomers saw this with the naked eye in 1054. And now, as we arrive into the 20th and 21st centuries, all of our Great Observatories and their successors have had key science results with it. So, you start with a supernova that sends debris out into the interstellar medium. Spitzer and Hubble made really spectacular, beautiful images. There's a beautiful set of Webb observations that is giving you detailed information on the compositions that allows you to trace back to the properties of the original star, incredible.

At the center of this is an extraordinary pulsar. This is a very unusual pulsar that is pulsing in radio, and x ray, and optical, and gamma ray, so it was a key result from the Compton Gamma Ray Observatory along with others. That pulsar is producing an energetic wind that is driving out into the medium that creates a shock when it meets the slower moving ejector, and that is where we find our galaxy's most powerful accelerator. This is where the most energetic electrons in our galaxy is produced. And Chandra observations and Hubble observations have imaged that region to allow us to see what's happening with spatial variations. And Fermi has allowed us to see what's happening at the very highest energies with rapid variability, and the observatories have worked together. Chandra and Hubble have done target-of-opportunity observations to follow up on Fermi results. So, I think it's just a really good example of how much science you can get from one small object in the sky when you use all of your Great Observatories together.

Domagal-Goldman: Awesome, thank you, Julie, and Giada, how about you?

Arney: Yeah, and I think mine is maybe the next one? Yeah, I thought. So, this one is not as incredibly spectacular as some of the other images, but I really love this one. So, this is actually a Webb image. This is HR 8799, and this is a photograph of another solar system, but it's different from our own solar system. These are hot planets, these are big planets, all of the planets that you can see, they're really big, they're hot. They're worlds in their own right.



When I was a kid, I got into space science because I was fascinated by the planets of our solar system. I'm still fascinated by the planets of our solar system, and it's incredibly amazing to me that we're now able to take these family photographs of other solar systems that are out there. So, I love pictures like this because they're just showing this amazing science. And as I think to the science to come with the Habitable Worlds Observatory, which is the mission I'm working on, we're going to be taking family photographs of potentially habitable planets that we just can't see yet. Mark mentioned the Hubble Ultra Deep Field, which is one of my favorite space images. The faintest galaxies in the Hubble Ultra Deep Field are about as bright as the potentially habitable planets we're going to be looking for. So, they're really, really faint fireflies next to their stars, and it's going to be really amazing once we can see them.

Domagal-Goldman: Thanks, Giada. I'm going to jump to a question for Knicole, which is how are—we're looking at this beautiful image of exoplanets. Actually, I'm going to pause first, yeah. How beautiful are these images? One thing I like to point out to people is our NASA calendars almost always have, in fact, every year I think they've had an image from Hubble, or from Chandra, or from JWST, and usually more than one. And that's because we know that there's a shared appreciation for the beauty of these images. But every single beautiful image we've taken, the beauty is just an ancillary benefit, right? It's the science that drives the observation. It's us, as humans, that are appreciating the beauty that comes out of that. I love when those secondary benefits come out. But looking at this one in particular, Knicole, there's a lot of connections between Hubble and

Webb scientifically. I'm going to ask Jane about this more broadly, but specifically in the exoplanet arena. How are Hubble and Webb working together to search for atmospheres on rocky planets?

Colon: Yes, that's a great question because Hubble, as we heard a little bit about yesterday, it really sets a stage with some of the first transmission spectroscopy measurements of exoplanet atmospheres. So when the planet is going in front of its star, we're not resolving the planet like we are in this image, but instead, we're looking at the star and the planetary system as just a single point source, but we can see the light filtering through the planet's atmosphere. And Hubble really set the stage showing us that there's a lot of water in exoplanet atmospheres, which water is abundant in the universe, and that is something we know is essential for life. So that was a great starting point.

And then Webb has really built on that by looking in the infrared at other carbon molecules, carbon dioxide, monoxide, and also seeing evidence of photochemistry. So, these photochemical reactions between other stars and their radiation interacting with the planet atmospheres of the planets that are orbiting around those stars. And we can see that even though these planetary systems orbit trillions of miles away from Earth. And these are just very tiny signals that we can see now with Webb that's building on Hubble.

So that's one aspect, but then also, there are programs like we heard about a bit yesterday, the Rocky Worlds program that's being undertaken right now to look specifically at small, terrestrial-sized planets. And look for evidence of atmospheres with Webb, but then simultaneously using Hubble to look at the host star properties, and use the ultraviolet light specifically to understand the radiation and what impact that has on the planet atmospheres. Because the big question with terrestrial planets, especially ones that orbit close to their stars, is can they retain an atmosphere at all? And so that's what we're trying to figure out. First, do they have an atmosphere; second, is there water; and third is, is it a potentially habitable environment? So, there's a lot of stages we have to take to get there, but, yeah, Hubble and Webb working together has already proven really fruitful.

Domagal-Goldman: Yeah, I love that story in part because the science you're describing with, well, actually, both HST and JWST, weren't the original driving science cases. In fact, we didn't know to ask some of those questions when those telescopes were being designed. Jane, I want to ask you, how did Hubble, in terms of its discoveries and the questions it made us ask, set us up? And I'm going to ask a similar question for Roman in a second. How did the questions that Hubble made us realize we should be asking, set us up for the James Webb Space Telescope? And then, Julie, if you don't mind, can you answer the same thing for the Roman Space Telescope?

Rigby: The last panel talked about the more sociological framework that set us up that I think is just as important. And so, I want to just underline and highlight that in terms of making this very professional, peer-review method of allocating the time which we take for granted. It's like the air, but it's something that, really, Hubble established as the standard that all the other observatories now follow. So, stipulating that as being just absolutely necessary to the science.

Webb was very much conceived because of the original Hubble Deep Field images. And in many ways, you can even look at the science case for Webb going way back, there were ideas that we would be staring at dark parts of the sky for days on end. And then, in fact, the astronomical community wants to point it at everything, we get more than 10 years of ideas every year we ask for time now, and so we looked at a lot of different things. And so, we will look at nearby planets, faraway planets, and then we'll stare at deep parts of the sky for days.

But in a lot of ways, the original Hubble Deep Fields are what really stoked that realization, just the realization that we could really study galaxy evolution, and that there was a place where the record went blank with Hubble just because of cosmological redshift, and we needed a redder telescope to go in and keep going. And then Spitzer, even though it was a much smaller telescope, really demonstrated that, yes, the infrared was very powerful, and, indeed, a 6-meter class infrared telescope was going to tell you the answer. And so, in a lot of ways, Hubble set that up. And then I think, it's also—so enough that it took a while to get to the point where Webb was finding things that we had never seen before, rather than—and that's happening now, that's really exciting. We're like, oh, we didn't know this kind of quasar—is it a quasar? We don't know. It took a while to get to that because Hubble had set us up in so many ways. The first year or so for extragalactic science with Webb was very much just continuing the Hubble legacy, but way out in redshift to the first couple hundred million years of the universe's history that we had never seen before.

Domagal-Goldman: Julie, can I ask the same question for Nancy Grace Roman Space Telescope? And also, if you don't mind, what questions has Hubble caused us to ask that has led to the Nancy Grace Roman Space Telescope? And I'll have a follow-up, I might come back a few more times, but you probably do this on the fly. What other science questions, because we're going to design Roman around that, what other science questions, once we answer those questions, will then enable us to answer as a scientific community?

McEnery: Well, I think for Roman, one of the driving discoveries was the accelerating universe. The discovery that the universe is not expanding constant with time, and it's not decelerating, but it's actually accelerating in its expansion, which is crazy. So then, that drives a desire to better understand the nature of the dark energy that's driving that. So that was a prime reason for a major, grand challenge science question that led to the concept of Roman as a mission to be able to study that very well. But in recent years, it's actually gone beyond that because you start with dark energy, and you develop a model of lambda, which is the cosmological constant, which relates to dark energy, and CDM, which is cold dark matter, which relates to dark matter that allows you to map the properties that we see locally in time with what's measured early from the CMB.

And a second mystery that's emerged is—I mean, we already realized we don't know what lambda is and we don't know what CDM is. But recent observations from Hubble and other observatories are telling us with things like the Hubble tension that, in fact, Lambda-CDM is not a perfect description of the universe. So, there's even deeper mysteries that Roman is going to be able to explore. So, Hubble has been the gift that's given twice because it first set the grand challenge question that Roman was designed to follow up on. But then it also raised a tantalizing, interesting mystery that Roman is incredibly well-suited to confirm and probe in greater detail.

Domagal-Goldman: Love that. So, Giada, a question for you, which is, what questions are we now set up to pursue and to be the driving questions for the Habitable Worlds Observatory? Once we design the Habitable Worlds Observatory around those driving questions, what other kinds of astrophysics or science questions will that enable us to pursue?

Arney: Yeah, thanks, Shawn. We've got this incredible legacy of these NASA observatories that I think, Matt, you phrased it as they're like civilizations' defining missions. They answer some of the biggest questions that we have in human history. And I think it's very clear, this legacy from Hubble through Webb and soon Roman are going to be part of this legacy.

I think one of the biggest unanswered questions in human history that we don't currently have the capability to answer, and I think that only a large flagship on the scale of what NASA can do can answer is this question, are we alone in the universe? Is there life on other planets? And it's a question that ripples through not just the scientific community, but of course, even through the public, and we see evidence of that in science fiction movies.

But also, it's something that captures the attention of kids. I used to work at a planetarium, and the big things that the kids would always want to ask about is black holes and aliens. Those are the two things that kids love. It's this question that has captured the attention of so many people around the world. And we're finally building an observatory that is being purpose-built from the ground up to address this question, are we alone in the universe, not just as a side goal, but actually a central goal. And I would argue that is the most ambitious question that has been designed around to be able to address for any NASA mission.

And so, it is a challenging question, I'm an astrobiologist, I could talk about how we're going to do that search and how we're going to interpret these planets. Certainly, it places a lot of technical demands on the observatory, and of course, it does, right? This is an ambitious and demanding question that we will need partnerships, right—we just talked about partnerships—to build these observatories that can address these questions. But in building this incredibly powerful observatory to address this fundamental question that has echoed through human history, we're going to be building the most powerful telescope that NASA has ever flown in its history of incredibly powerful telescopes in this legacy of flagships. And so, this observatory will be able to tackle new questions in astronomy, and astrophysics, and planetary science that we can't yet address, right, with other facilities. Building on this legacy that you've heard about here at this Hubble celebration and with Webb and with Roman, answering new questions that we can't yet think of in astrophysics.

So, we're going to be able to study galaxies, and galaxy formation of stars, and star formation, galaxies in the early universe, galaxies in the local universe. The universe will be your oyster, not just for this facility, but for NASA flagships in general. But for HWO specifically, we are certainly thinking about the amazing astrophysics that we will be able to do alongside a game-changing astrobiology that we want to do with this mission.

Domagal-Goldman: Thanks, Giada. Mark, you wanted to jump in?

Clampin: Yeah, I just wanted to make a comment. So, we're here talking about legacy and what can we take from Hubble and also Webb to what we do next. Jane talked about the role of the deep fields and how they led to the Webb telescope. And I just want to give a shout-out to Holland Ford who, in '92, wrote a proposal to do deep-field imaging with the Advanced Camera for Surveys, and I said yesterday the Hubble Deep Field was '95. So there was a lot of vision there, and he incurred the ire of a lot of the community because to do that, he really focused the camera's performance on doing that science long before it was a thing.

And I think, as we talk about what are we going to do with Habitable Worlds and how are we going to design it, that's the kind of laser focus that we're going to need to make sure that Habitable Worlds could work because it's a very challenging problem. It's much more focused problem, for instance, than we had with Webb where we were just trying to find the first galaxies in the universe, and it's a much broader and wider problem. I'm not saying it was any easier, but when you start talking about looking for specific biomarkers and seeing planets at very close distances to their parent stars, that 10-to-the-minus-10 contrast, those are very focused problems, and they will require laser focus from the science community to make it happen.

Domagal-Goldman: Thanks, Mark. Actually, my next question was for you, which is—I'll set it up by saying this. It's clear, I think, to me, to everyone in the room, the power of these flagship observatories. I'm fond of saying that they make the impossible routine. Things that we couldn't imagine that we could've done before are now just part of many people's time allocation proposals, and when we often do things weekly or monthly, that would've been otherwise impossible. But that's hard and that's expensive, and to do new impossible things requires us to find the resources to set aside for them. And we've heard a lot from, I think, both yesterday and then over the course of the past few months, that we're driven to find efficiencies in everything we do at NASA, and especially in, I would say, the most well-vintaged observatories that we have in our fleet. So, what are our plans for that that you can speak to, Mark? What can we say about our plans to find efficiencies here at NASA for our existing observatories? And I think I would ask you to put this in the context not just of astrophysics, but all of science at NASA.

Clampin: So, the administrator laid out a kind of road map or a directive on May 22nd, and you can go and read that. And at the bottom, after all the organizational changes and leadership changes, you'll find specific direction to each of the mission directorates. And buried in ours, I think there are several things that we are thinking about within the Science Mission Directorate right now. So, one of those is how can we get to science faster, and the ways that we're thinking about that are changing the way that we work with industry. Finding different ways to do procurements with industry and work with industry so that we can get more standardized interfaces, for instance, so that we can get payloads on buses more quickly. So, certainly, a big part of this is thinking about how we do procurement right now and how we can speed up the whole process.

Tied into that, we also have the competition model. And one of the things that we're looking at right now within the Science Mission Directorate is can we change the whole competition model for the smaller missions and up to the mid-class missions, and do those differently? So that we can actually maybe produce a fairer playing field, make sure that we're providing the right level of guidance for any PI that has a great science idea that gets selected so that we can move forward with them. I can't give you more details right now, but we'll be starting to socialize the changes that we're making fairly soon.

The other area where we're being urged to think about making changes by the administrator is looking at how we do mission operations and also the related science operations. And I spoke yesterday at some length about what I see as the value of science operations. So, we're starting to think about how we do that, and as we get missions into their extended life, which means out of the nominal prime mission, how we can look at making changes to mission operations and some of the science operations as well. So that we can reduce the cost of operating them, which means in the end game, we hope we can get the same kind of science return at a cheaper cost. And these are all directions that we've received from the administrator, and I think you'll see when you read through the directive that we have 60 days to put together the plans for these different elements.

The one thing I didn't address, which is also very relevant to this meeting, are large missions. And the expectation is that we will still direct very large flagships, certainly astrophysics flagships, but even there, we're being asked to think differently about how to do them. I think everybody would agree that Webb is a great telescope, but it took a long time to build, and we really want to do Habitable Worlds faster. So, finding new ways to think about Habitable Worlds is really important too.

And one of the ideas we bring from Hubble is servicing, so you don't have to build the whole observatory at once. Habitable Worlds will be basically a room-temperature telescope, we're not going to cool the primary mirror, so that means that we can service it. It's not like Webb where the whole telescope is giftwrapped multiple times in MLI, and you can never get to the instruments because of the requirements of running it at cryogenic temperatures. Habitable Worlds is not like that. We will be able to build it from day one to be serviceable, so we can do incremental upgrades, which means that we can focus on getting it to orbit more quickly and then do incremental upgrades, as we've done with Hubble, over time to the instruments to achieve all of the science goals that we want to achieve.

Domagal-Goldman: Right, thanks, Mark, and I'll use that to transition to a question for all the panelists. Finding those efficiencies for astrophysics right now is particularly important. We've got a probe mission that we're currently under review—concepts that are currently under review, we're making a decision on that later this year, those are billion-dollar-scale observatories. By the way, those probe concepts will expand the wavelength range from the flagships that are represented here on the stage. We've also got LISA, which will extend beyond wavelengths into the gravitational wave arena, where we could hear or feel the universe in addition to seeing it, and, of course, the Habitable Worlds Observatories. So, we have separate missions at this about $1-billion or higher investment level, especially when you include the investments of partners, which both makes it important for us to find efficiencies to afford that future science. And it means that the lessons from these past flagships are really important. So, my question for the panel is, what are the lessons that we've learned from these observatories, they could be technical, programmatic, scientific, whatever you like—yeah, Julie —that would apply to these, to LISA, to HWO, to a future probe?

McEnery: So, I think when we're talking about science operations, it's important to not think of efficiencies simply as saving money. You can make an efficiency by doing more, by innovating, doing new things that then lay the path for future missions to immediately jump on that innovation and get it in from the ground up so that operations for future missions is cheaper. So, for example, in the current climate, I think as we're seeing more and more influence of AI, several missions have incorporated aspects of that. And I think it is useful to consider innovation in existing missions as laying a pathway for good things that we're going to do in future ones.

Domagal-Goldman: Awesome, thank you, anyone else?

Arney: Hello, hello, I guess two threads, which is—right, so servicing, right, is one of the things Mark brought up. We've seen the power of servicing with the Hubble Space Telescope. It makes a whole new observatory when you bring up new instruments. So that's certainly something we are leaning into with Habitable Worlds Observatory. I'm personally very excited about the possibilities of servicing and ways that servicing could help to put HWO on the launchpad more quickly.

I think the other thread is learning these lessons learned from other NASA flagships and how to do them better. There's even been an internal study at NASA, the NASA Large Mission Study, that looked at how do we do NASA flagships better, how do we do them more quickly, all of these things. And so, we're trying to follow that guidance on HWO. Because we're very early in the mission life cycle, one of the things we're trying to do right now is something that was highlighted in that report is early technology development. So, if you mature your critical core technologies early, that can save you time and money later because you buy down those risks. You don't want to have risks pop up later from immature technologies, you want to get those technologies to a certain level of maturity early on, and so we're doing that right now. We just funded seven industry teams who are going to help us mature some of these critical core technologies for HWO. So, those are a couple of things that we're thinking about.

Domagal-Goldman: Jane, did you have one? No? Okay, got it, anyone else? Mark?

Clampin: So, I mentioned servicing, and I'll just add to what Giada said. We attended the annual Space Symposium a few weeks ago, and you wouldn't believe the number of companies or startups who were talking about doing servicing and space refueling, assembly in space. So, there is a very big demand for this kind of capability. Most of it doesn't come from NASA, it comes from other federal agencies, but that is a capability that we can ride on their coattails and achieve the goals that we want. So, we are very enthusiastic about that.

A couple of other things that I think are really important. I mentioned one is really build on your tech, technical investments, and we've done that with Hubble and then Webb in detector development all the way to Roman. But there are equal or very similar ways of building on the investment that we've made in optics and metrology and actually building large optics and being able to do very accurate measurements of their surface figure. And that started with Hubble. I mean, the whole impetus to develop phase retrieval to the level that it is now started with trying to understand, did we have the right figures on the Hubble correction mirrors when we were getting ready to figure them? So, we need to build on those.

And then the other one I'll just mention is when Hubble launched, its ground system was really groundbreaking. Nobody had ever done anything like that. So, we also need to keep thinking about how we innovate on our ground and science operations systems, so we're providing the maximum level of value to the science community. And there are a lot of new ideas out there about how you incorporate AI into clouds that take you all the way from the telemetry to science products. And again, when Hubble launched, the idea that you had a pipeline that would give you a fully calibrated image you could just download and start doing science on was revolutionary. And that is one of the things that's really made Hubble so productive and successful. So, innovate in every part of the lifecycle of the mission.

Domagal-Goldman: Awesome, thank—oh, yeah, go ahead, Knicole.

Colon: Yeah, I just wanted to add one thing about, too, a high-level, getting public support and messaging of all these missions. Of course, we're here because Hubble has such a legacy, 36 years in space. And it came up yesterday with things like Hubble and the Apollo mission, how do things like Webb, Roman, HWO, Artemis live up to these legacies? And especially because we're in this era of information overload, social media, everybody gets news so quickly, we have to find new ways to just keep innovating and connecting, I think, with the public and learning what made, again, Hubble, Apollo so successful. And just building on that to keep maintaining support because a lot of this, it's all going back to the taxpayers in the end.

Domagal-Goldman: Totally agree with that. Any questions from the audience? Oh, yeah, ding-dong, time for audience questions. Do we have anyone out there? Yeah?

Audience Member 5: Yeah, no, I'm a big advocate of making sure Hab World is serviceable. Because I think the legacy of Hubble is that if we invest in the right technology and partner with the right industries, we can make this future telescope last for generations, and that would be great. Just a quick comment on the inspiration for Roman, I agree with Jane that HDF definitely was the inspiration for Webb. And I think we have to give credit to our ground-based colleagues because the discovery of dark energy was a ground-based discovery, Hubble just confirmed it. And the other thing is that I think for Webb, the lensing observations, both your work, Jane, and CLASH, and Frontier Fields allowed us—even though Hubble couldn't get to z of 14, it got us to z of 11. And we knew that once we broke that z of 10 barrier, that Webb was just going to have a lot of science to do. So, I just wanted to make that point.

Domagal-Goldman: Yeah, for the panel, are there favorite team-up stories between observatories or between the ground and space that anyone would want to highlight? From a flagship and a ground-based observation or a flagship and a smaller observatory? We heard a couple on the images described about before.

McEnery: An immediate example is that both Roman and Rubin were top-ranked in the same decadal survey with the intent that they'd be synergistic with each other from the beginning. So, on Roman, we have defined our major surveys in the context of knowing that Rubin was going to be there. So, we're two big things synergistic by design from the decadal survey recommendations all the way to the present day.

Domagal-Goldman: That's planned, not serendipitous synergy. Oh yeah, Mark, go ahead.

Clampin: I would just mention, and I touched on it the other day, but the very first Hubble spectroscopic observation of a transiting exoplanet, 209458, came from the work that Dave Charbonneau did out in Colorado, where he actually did one of the very first transit observations with a Celestron in a car park outside at NCAR, I think it was. And it was very soon after they did that observation that they wrote the proposal to do the Hubble observation.

Domagal-Goldman: Awesome, I'll add one of my own before tossing to the next audience question, which is, I think it was Spitzer that finally honed down the location of potentially habitable exoplanets. And the first ones that we definitively identified as being in the habitable zone of another star, that made headlines across the world, I think, in 2016. But that was, again, only possible from the combination of multiple observatories, including on the ground and multiple space. And Spitzer, who's another flagship that we just don't have a project scientist up here on the stage for, is the one that brought that one home.

Rigby: I think that's a point we need to keep making. That it's an ecosystem, and that these Great Observatories are not the divas that stand alone, there's a chorus. And when we look at proposals in this intensely competitive proposal process, one of the basic questions the panel asks is basically, have you done your homework? Have you obtained and analyzed the data on every other observatory already that would answer any of these questions that you can? And now, all that is left is uniquely Webb or Hubble can now do this work? It's almost like it's assumed; otherwise, your proposal is going to fall on the floor. So, it's assumed that there's an ecosystem. I think that's something that can get lost when we talk to the public, but really, it's why there has to be a portfolio. And when I explain to the public, it's usually as simple as we need to know where to point it, and that resonates, right? But I think that argues for the whole suite, we're not standing alone, we're working together as an ecosystem.

Domagal-Goldman: Yeah, and that's also important for how we develop our next telescopes. Someone asked me cynically, "What do we need another space telescope for? Don't you have all the beautiful images you need from James Webb?" And I said, "Well, thank you, yes, we do have a lot of beautiful images from the James Webb Space Telescope." And those images were taken to pursue science questions that we wouldn't be able to pursue without a James Webb Space Telescope. And the Nancy Grace Roman Space Telescope is going to take different kinds of beautiful images to pursue different kinds of science that JWST and other telescopes can't pursue, and that'll be true for HWO and so on. But let's go to the next audience question.

Julie Crooke: I have two separate questions. I'm curious from each of the reps from each of the flagships here. Scientifically, what is the percentage of either, in reality or projected in the future—although Hubble, obviously, has a lovely advantage here, in terms of the percentage of scientific questions that these flagships answer that were proposed originally versus evolved over time and we're able to do it? That's my first question. My second question is more—

Domagal-Goldman: Let's take that question, and then—but feel free to stay there and ask your second one after, Julie. So who, any answers to that? I thought I saw a knowing smile from Julie.

McEnery: I've got no idea. But I think it is the case for any mission that the ideal science case is that you have some number of really compelling scientific questions that you are definitively going to be able to answer or make a significant contribution. And that you've got significant discovery space so that you are opening the floodgates to finding the things that will address a new set of questions for both your mission and the future missions to explore.

So, for example with Fermi, one of the major driving goals was to find the particle nature of dark matter. But what it actually did was discover a large population of gamma-ray pulsars in our galaxy, and that the excess at the galactic center is, in fact, is not dark matter. It's a previously unknown population of very energetic pulsars, and I'm confident that Roman is going to find surprises. It's what makes me so excited about the mission because our observing pattern is to just look at large regions of the sky to find all the things that are there, both in time and space.

Rigby: I like that Isaac Asimov used to say that the sound of scientific progress is not, "Eureka, I've discovered it," but "That's funny." And I think that's often true. Sometimes, it is the, I am trying to find this particular low-hanging fruit, and by George, I've found it. And I think Webb has done exactly what we said we would do and we've shown that, but for me, the part that's the intellectual curiosity is really fed by that, "That's funny." That's part of the humility of science is that we're led where the data and the universe take us. I mean, who would've believed in dark energy before we had it? It's absurd, it makes no sense, and yet, it's what the data say is happening. So, I'm really looking forward, too, for Webb's extended mission, exactly that. That increasingly, most of our science focus is going to be things that it's where the prime mission left off, that it's the stuff we didn't know was out there to go follow up on, or we're doing some of the same big fields like exoplanets, but taking it really to the next level.

Arney: On HWO, we always like to say that we want to be able to address questions that we can't yet dream of, right? Because, again, this is the legacy of these NASA flagships, is we build these amazing and powerful facilities, and then people like Jane or other astronomers look at the data, and they're like, "That's funny," right? We didn't know, we didn't even think to ask the questions before we got the data because we're seeing the universe in new ways with new eyes that it defies our human imagination, how creative the universe is.

I think specifically with exoplanets and habitable planets, which is my field, we currently have one example of a habitable and inhabited planet, and we're sitting on it, right, or standing on it and breathing the air on it. So, when we get another example of a potentially habitable planet, I think we're going to be excited, but I think it's also going to take us some time to figure out what we're looking at. Like Jane said, we're going to be like, "That's funny"; we're going to discover surprises. The history of astronomy and the history of exoplanets is a history of surprises, of discovering planet types and planet properties that we couldn't imagine existed until we discover them outside of the solar system. And life and habitability are such complicated processes that we're just beginning to understand. That when we finally have that data of another example of a potentially habitable and inhabited world, I think we're going to be like, oh, my God. But I think we're also going to have to take some time to unravel our confusion about what we're looking at before we feel truly confident, and it's going to be really exciting.

Colon: And I'll just add building on exoplanet's theme because that is definitely a field where the community is literally bombarding both Hubble and Webb with proposals, and I think more than anticipated perhaps. But what we've seen with the actual observations, especially with Webb working so well in providing us this exquisitely precise data, is now, we've revealed limitations in the models. And so, it's really pushing the modelers and the theorists to understand the stars more. The stars are not quiet, and so they're a nuisance to when we're trying to study the small planet atmospheres, specifically for the transiting exoplanets. But, yeah, there's limitations now and enhancements we need in the models, but also in our laboratory work, the same thing. It's we're really pushing the boundaries with the observations, and so now as a result, we're pushing boundaries with the models. The whole community has to come together and continue to work together and to keep making progress.

Domagal-Goldman: Julie, I think there was a second question you had and other audience member questions, feel free. Yeah, go on up, go on up Jennifer. Julie, do you mind holding onto your second question, while we've got other audience questions?

Jennifer Weisman: So, I want to talk about science selection. As you just mentioned, Knicole, we're getting inundated with proposals, JWST, of course, and Hubble got more proposals this cycle than last year, so we're still at a six to one over. So my question is, regarding the influence of Hubble, the whole science selection process has been a growing, changing art form in and of itself throughout Hubble's mission. How do you decide which proposals to accept? How do you decide how to distribute small, medium, large proposals? How do you decide which science categories to have panels to evaluate? How do you decide how much should be for just blue-sky observations, mainly that's given to the Director's Discretionary Time? So, I guess we're still working on this in Hubble, right; we're still changing. The biggest paradigm change was the dual-anonymous reviews, right, which we've already heard has made an astounding change in the kinds of teams that are able to get time. But that did not come without controversy about whether or not we should do this.

So I guess I just want to ask how you feel that the legacy of Hubble's learning about how to choose which science to do—and we're still learning, how is that affecting your plans for newer missions and future missions in terms of science selection to make sure we're getting the best science possible out of these flagship missions?

Domagal-Goldman: I've got one if the panel doesn't, but if you want to go first, Jane, you can go.

Rigby: I love that you asked that, Jennifer, because I have on here, make sure to talk about exactly this. Because I think it's something that it's easy to take for granted, Hubble's legacy, because it's the water that we're swimming in, and yet, it is a constructed process. And it's something where the Space Telescope Science Institute has built such a legacy of this incredibly professional proposal review. And a process of experimentation, of experimenting with things like dual anonymous, which I think has really been good for the field in bringing a sharper focus on the science rather than the personalities. And things like how do we do programs so big they don't fit in a year, how do we—? So, I think we're very much building on that legacy.

I think that it's also something where when I talk to the public about this, they are always surprised that this is how we do it. They assume it's a dark-field room, or that the most powerful people get all the time, or that it's some sort of cronyism. And I think it's something that we need to be better about explaining because it's really a triumph of how we do things. And there's always room for improvement and continuous improvement, but it is fundamentally something that I think is a real strength of the whole process.

Domagal-Goldman: Yeah, I'll go quickly here. I'm going to broaden out that. The other one I'm aware of is the Chandra X-ray Center. It's currently conducting an experiment of something they're calling distributed peer review. And one of the things I like to make an analogy is, sometimes, we talk about the state's legal and lawmaking standpoint being engines of innovation. And I think having these three external science centers, Chandra X-ray Center, which I mentioned, the Infrared Processing and Analysis Center, and the Space Telescope Science Institute, not be locked into the processes that we have at headquarters across SMD where making a change can take some time. They have the freedom to innovate and experiment, and the good ideas will pull in and, sometimes, will affect not just our astrophysics observatories, but all of SMD. And so, I really appreciate having those engines of innovation in our ecosystem.

Questions from the audience that aren't Jennifer and Julie? And it's okay to have more than one; I just want to give others a chance first. All right, Julie, let's go with yours and then Jennifer's, and then unless others come up, I've got a closing question about the future for the panel.

Julie: All right, so going back to the Hubble thread and its servicing missions, which are in the low-Earth orbit by astronauts, of course, and going towards the future with HWO and the relative skepticism by some people. My question is, do you think we should just let industry take off, or do you think there would be a useful low-Earth demo of doing—? There have already been lots of demos like close-proximity ops with CEV, the ISS, and all these things, refueling. There's already been lots of servicing demonstrated in space. However, my question is, do you think there are additional needs of demonstrations in space that could be done on a CubeSat with mating two things, or is it something which we could just let industry take off?

Domagal-Goldman: I've got one I'm quite eager to talk about, but I'll see if the panel does first. To unlock servicing for HWO, I think one of the keys is for it to be something that we're more or less procuring as a service, and that it's not an agency-developed servicing capability. And right now, we've got an amazing team in Katalyst partnered with Northrop Grumman that's racing towards the launchpad to do just that, to show servicing as a service, to grab on to Swift and boost it to a higher orbit. And if that succeeds, that's not just a technical success from my standpoint, but a programmatic one that's very much HWO servicing enabling.

Clampin: So, Julie, I'll just say this is a great example of when you see science as a service and the administrator talking about science as a service. This is the kind of thing, for instance, that we're thinking of that come under that rubric. And from my perspective, as Shawn said, we are doing some things that are part of the SMD portfolio, like re-boosting Swift. And while that may not be the dictionary definition of servicing, it certainly gets towards what we want to do.

And there's a multibillion-dollar investment in other agencies. There was an article just a few days ago, the U.S. Space Force is investing a colossal amount of money in servicing capabilities. So, I think we can sit back, buy popcorn, and watch the show, and when we're ready to start work in that part of the program, we can pursue these science-as-a-service opportunities with the companies that are doing the work right now.

Domagal-Goldman: And, Jennifer, apologies, I think I'm going to preempt your second question to ask a final question on the panel, is that okay? I did put an elephant in the room by mentioning re-boost or boosting of Swift, and I'm sure that there are people in this room that care deeply about Hubble that have that question. What does that mean for this observatory we've been talking about the last two days?

I'm going to refer back to something that Mark was speaking on and I was speaking on before, which is I think when we made the decision to boost Swift, we did that in the context, I would say, of a few specific things. One, we were weighing the ROI of boosting Swift compared to replacing it. And I think it's clear boosting and extending the lifetime of Hubble compared to replacing it is a good buy, especially because most likely, we're going to have to do something with Hubble at some point before it comes out of orbit. Just because it's so darn big and heavy, I don't think we're going to be bringing it down uncontrolled.

But then the second part of that is making sure that we can afford the long-term investment in the ground operations. The integrated expenditure we'll have on continued operations for Hubble is likely going to be larger than the re-boost itself, especially with the way that these servicing companies are offering these capabilities at a lower cost than we previously estimated. And so, the real question on an ROI is not about the boost itself, it's about how much are we going to be spending integrated over time by extending the lifetime of the mission? And how does that fit into our portfolio when we want LISA, and a probe mission, and Habitable Worlds Observatory, as well as a bunch of smaller explorers missions in the portfolio as well? That becomes the real challenge.

I'm going to end on a bright—I know we're at time, but I want to ask one quick question for the panel. This is the very first question I asked the astrophysics team when I started this job a year and a half ago. And for those that are here, just take mental notes on the answers from this team. Hubble launched decades ago, still operating today. We are hoping that the observatories represented here on stage, some of them will be operating decades into the future. Pretend it's year 2060, yes, so a Hubble's time from now—a Hubble Observatory's time from now, not a Hubble time for now, what do you want to see? Instead of the world you want to be in really, what's the universe you want to see by 2060? What things are we aren't doing today are you hoping that we're doing in astrophysics? Mark, you first.

Clampin: Then the silence, but I will talk about something I've really been excited by over the last couple of weeks. So, every now and again when I talk about Habitable Worlds and the possibility that we'll find a planet where we think there may be evidence for life, people always ask me, "What comes after that?" And one of the things I will just point to is an area that we're really focused on right now—I've talked to Matt about this in the past—which is how we can use quantum technologies in the future. And somebody just published a paper—and I cannot remember the name of the author—just a few weeks ago in *Nature*, showing that you can use entangled photons to phase interferometers. So in answer to what comes after HWO, and I'm just speculating here, think about an interferometer where the separation between the spacecraft is millions of kilometers and the angular resolution you get, and you phase them using entangled photons, so a super, super high-resolution telescope.

Domagal-Goldman: I think I remember you sending me that paper on email, and the email just said, all caps, "WOW!"

Clampin: This is a really big thing, and the administration is currently focused on making a lot of investments in quantum technology. So, you can expect to see it on Habitable Worlds Observatory with sensors, and this is something to think about for the future.

McEnery: So, I'm really excited by the journey we're beginning with LISA. We're opening up an entirely new way of exploring the universe, and we've got no idea, really, what surprising things we're going to discover. What we know we're going to find is exciting enough, and LISA is just the beginning, it's the first observatory of its type. And opening our eyes in an entirely new way could mean that by the time we get to the 2040s, we have a dramatically new vision of the universe that we live in. And I'm very excited by that and by the future observatories that will be motivated by those discoveries. And to follow on from Mark, atom interferometry is a key technique for some directions in future gravitational wave observatories.

Arney: You know, are we alone is one of the most significant questions in the history of humanity. And the thought of actually having an answer to that question, which we might, we might have that with HWO by 2060 or before 2060, hopefully. I think it will be one of the most significant discoveries and one of the significant moments in human history of knowing more about humanity's place and Earth's place in the universe. And so, it's hard to imagine that that will have ripple effects of exciting people about space, exciting people about science. People will want follow-on missions. People will want to know more about this universe that we inhabit and that we know we're not alone in. People might want that interferometry mission that Mark was just describing so that we can learn more about the universe and maybe learn more about that habitable world out there. Actually resolve its surface, maybe see oceans and continents on its surface so that we can study it, not just as a habitable point of life, but as this habitable world that we can resolve features on. It's hard to know how humans will respond to such a game-changing discovery and such a history-making discovery. But I'm confident in saying that I think there's going to be a lot of ripples throughout the world in response to that discovery.

Rigby: Can I add 200 years to your question?

Domagal-Goldman: Friendly amendment accepted.

Rigby: Well, yeah, I was reading a science fiction novel the other day, which I don't normally read, and they were trying to characterize quickly a civilization like who are these people, what are they capable of? And it mentioned that they had eradicated some of their major diseases and built space telescopes, full stop, and I loved that. It's a very short way to say, what is the progress of this civilization? And that builds on something that Matt said earlier.

I do think that these things are going to outlive us, and they're legacy, and some of that is just who we are as humans and what's the best that we've done. So, some of that is looking back in a couple hundred years, I think we will see Hubble as the first time that we gained that ability to do that, that's really, we want to keep being a species that does that. If I get to live to the 2060s, I hope we know what dark energy and dark matter is. It's just embarrassing that we still don't know what 96 percent of the universe is made of. I'd really like to have that answer before we die.

Colon: And I will continue to build on the exoplanet theme, I am an exoplanet scientist, I didn't mention that. But it's wild to think that in Hubble's lifetime, that's the same amount of time we went from discovering the first exoplanets to knowing they're literally everywhere in the galaxy and most likely everywhere in the universe. We now know of over 6,000 over the past 36 years, and it's wild to think that in the next 30 years, we could be finding Earth twins and actually understanding their atmospheres and seeing if any are inhabited at all. And so that's a very rapid timescale of evolution. I'm hopeful that by the time we're in 2060, we are now at the phase where we would be developing dedicated missions focused on following up specific Earth twins, whatever that may look like. So that's one avenue that I would look forward to in the future, which also would be around the time I'm retiring I think.

But that and then also seeing what, if any, routine astrophysics we would be doing from the Moon by then, and/or Mars, or spreading out into the solar system a bit. I don't know what that looks like, but it's definitely fun to think about. And so, yeah, again, building on the Hubble legacy and the timelines here, again, there's been so much rapid evolution over the past 36 years, and so a lot of what I think the big picture of what we'll see, like Giada said, are things that we don't actually know what questions to ask yet. We need more data to say, "Oh, that's funny," right, and then to keep following it up. And maybe some of that will involve looking at Earth twins and being like, "Oh, that's funny, there are aliens waving at us."

Domagal-Goldman: I love and I want all of those things that we just heard from all the panelists. And for the Astrophysics Division team members in the room, I hope you're at least taking mental notes because that's our job to go make all that stuff happen. To everyone else in the room, thank you for letting us go a little over time, and let's thank this amazing panel. So, it's been a great two days thinking about the wonderful past we've had with the Hubble Space Telescope, the great present we've got with that observatory, and the future that we've got not just for Hubble, but for all the observatories we're hearing about today. I think it was nice that we're able to close out with some thoughts far off into the future where, to paraphrase some of the panelists, future astronomers will be going, "Huh, what is that?" about gravitational waves and dark matter and dark energy and the question of are we alone. So, let's go make all that happen together as a community, huh. Thanks everyone for your time, and I hope you enjoyed the last two days, thanks.

[End of Symposium]

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